EFFECT OF SOLID CATTLE MANURE AND LIQUID HOG MANURE APPLICATION ON PHOSPHORUS AND NITROGEN IN SOIL, RUN-OFF AND LEACHATE IN SASKATCHEWAN SOILS

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By

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ABSTRACT

Traditional application methods in which manure is simply broadcast on the soil surface are being replaced by innovative methods that place the manure in the soil in bands, potentially increasing efficiency of manure nutrient utilization by crops and reducing losses to the environment. Limited information exists on the pools and mobility of phosphorus (P) and nitrogen (N) in soils receiving repeated applications of animal manure using different application methods. The overall objective of the thesis research is to determine the fate of manure nutrients applied using new subsurface banding technology, as it affects crop response and uptake, residual nutrients in the soil, and transport (lateral and vertical) by water off-site. Specific objectives were: 1) to determine yield response to solid cattle manure (SCM) and the recovery of SCM and liquid hog manure (LHM) P and N using broadcast manure placement and new subsurface banding technology, 2) to determine the amount of soluble reactive phosphorus (SRP) and N that is transported in snowmelt water moving across soils receiving different rates and methods of application of manure, and 3) to determine the amount and proportion of SRP and N that are transported downward in a SCM amended soil profile with leaching water as influenced by manure rate and placement. In-soil placement of SCM in bands had a small impact on improving crop yield and nutrient uptake in a 3 year crop rotation in east-central Saskatchewan compared to broadcast, and broadcast and incorporate application strategies. In-soil placement of manure was also not effective in reducing P and N export in snowmelt water. Export of P and N downward in leachate water in intact cores was increased by in-soil manure placement, especially when placed in bands. This is attributed to reduced fixation of manure N and P and enhanced solubilization when manure is placed in soil in bands versus a broadcast application. Overall, nutrient export was significantly lower in frozen versus thawing soils, and export of P in soils receiving liquid hog manure was much less than in soils receiving solid cattle manure which is attributed to the higher P content in cattle manure.

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DEDICATION

I dedicate this work to my parents Allen and Jeanette King and to both my brothers William and Colin King. The assistance and patience afforded me by my family over the last several years have been second to none and only a graduate student's family can remotely empathize with the selfless sacrifice of time, energy, and finances these family members have made in support of my academic endeavors. Although my Mom departed this world before I began my Ph.D., it was her dream that I embark on this arduous and difficult process. I love all of my family immeasurably and have been truly grateful for your help, although I always had a difficult time expressing it. I also have to dedicate this Thesis to "My Guys", Cudworth and Muenster. Although they usually did more to hinder the work process than anything else, their presence and antics were a tremendous source of stress relief and always brightened my day no matter how bogged down on the thesis I had gotten by the end of the day.

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LIST OF ABBREVIATIONS

C	Carbon
LHM	Liquid hog manure
LSD	Least significant difference
MK	Modified Kelowna
N	Nitrogen
NH_4-N	Ammonium-nitrogen
NO_3-N	Nitrate-nitrogen
OC	Organic carbon
OM	Organic matter
P	Phosphorus
PAMI	Prairie Agricultural Machinery Institute
PO_4	Phosphate
PO_4-P	Phosphate-phosphorus
SCM	Solid cattle manure
SOC	Soil organic carbon
SOM	Soil organic matter
SRP	Soluble reactive phosphorus
TN	Total nitrogen
TOC	Total organic carbon

1. INTRODUCTION

1.1 Use of Animal Manure to Fertilize Annually Grown Crops

Land application of animal manures such as solid cattle manure (SCM) and liquid hog manure (LHM) is a common practice in annually cropped fields, forage and pasture lands in western Canada and other areas of the world, to increase soil fertility. Statistics Canada estimated there were 2.3 million cattle and calves and 1.17 million head of hogs on Saskatchewan farms as of January 1st, 2015 (Statistics Canada, 2015). The manure is valued for its content of organic matter and constituent nutrients, especially phosphorus (P) and nitrogen (N) to increase crop yields (Bernier et al., 2014). The application of SCM and LHM to land is both a lower cost nutrient application alternative to commercial fertilizer, and a means to dispose of animal waste and recycle the waste constituents back into the soil-plant system. The manure constituents serve two purposes: the first is to add organic matter (OM) back to the soil system, thereby adding to the resident soil OM, which serves to store and recycle nutrients and water, essential elements for future plant growth and longevity; and second, to return nutrient elements such as P and N back to the soil where they may be utilized again by plants in future seasons (Campbell et al., 1984; Miller et al., 2006; Sommerfeldt et al., 1988). It has been described that the application of animal manure, particularly solid cattle manure, aids not only in supplying nutrients to plants, but has indirect effects on plant root growth by increasing soil aeration and porosity (Schoenau and Davis, 2006).

Application of animal manure to provide nutrients for plant growth has been a long accepted crop management practice in Canada and other regions of the world. Yield responses to the nutrients contained in SCM and LHM application at several sites in western Canada have been quite favorable (Mooleki et al., 2004; Mooleki et al., 2002). For example, in Saskatchewan soils, part of the plant yield response to animal manure has been attributed to the P contained in the manure (Qian and Schoenau, 2000) or micronutrients such as zinc and copper, particularly if there is a limited plant available soil supply of those nutrients (Lipoth and Schoenau, 2007; Qian et al., 2003).

Application rates of manure to agricultural lands in the past have traditionally been N based (Gburek et al., 2000), owing to this nutrient most often being the major limitation in crop production. However, animal manures such as SCM and LHM contain significant amounts of other plant nutrients like P. The nutrients in animal manures can vary in availability and transportability in the soil depending on source (Beauchamp, 1983; Eghball and Power, 1999), differences in animal nutrition, differences in animal containment facilities and manure handling practices (Mooleki et al., 2004). Any one or a combination of these factors act to produce manure which has a distinct composition relating to the forms, amounts and behavior of nutrients present in the animal manure.

For example, some studies have shown that N availability in the year of application can be low, depending on the animal manure source (Beauchamp, 1983; Pang and Letey, 2000), especially for some solid manures. This is related to the presence of much of the nutrient in an organic form, thus requiring time to be converted into a plant available form (Mooleki et al., 2004). In order to meet crop requirements for N, there has been a tendency to apply the manure in large amounts to compensate for this factor. However, in order to meet plant requirements for N, other nutrients, specifically P contained in the manure, may end up being over-applied in amounts that exceed the plant ability to utilize all the nutrient (Sharpley et al., 2002). This can have adverse environmental effects, in that excess nutrient could potentially be exported from the soil via water runoff and/or leaching (Kleinman et al., 2000).

1.2 Environmental Concerns with Soil Nutrients Arising from Animal Manure Application

The expansion of the intensive livestock industry in western Canada has led to concerns about the overloading of P and N in soils receiving animal manures. In areas that receive high application rates of animal manures, elevated transport of dissolved and particulate P and N by water can be of concern in nutrient overloaded soils (Kumaragamage et al., 2011; Sharpley, 1997). For example, since the 1990s, soil P levels in Manitoba have increased due to manure application, and agricultural sources have been identified in the popular press as responsible for supplying a significant portion of Manitoba's P loading into Lake Winnipeg (Kumaragamage et al., 2011). High P levels in water bodies can lead to eutrophication and algal blooms. Eutrophication, which depletes surface water bodies of oxygen due to increased growth of algae and subsequent decomposition, is accentuated by the export of P nutrient into the water and is identified as a major concern in Manitoba (Kumaragamage et al., 2011). Nitrogen export off-site is also of concern, as for example this can lead to health effects in humans such as methemoglobinema from consuming water that is high in nitrate-N (NO_3-N). It is estimated that P export from annually cropped fields in Manitoba contribute an estimated 15 % of the P in Lake Winnipeg (Kumaragamage et al., 2011). Application of animal manures that contain P in rates that exceed crop nutrient requirements can lead to an accumulation of P that is susceptible to water export (Hao et al., 2008; Reddy et al., 1999; Withers et al., 2001).

Applying animal manure based on crop nutrient requirements and utilization potential would aid in minimizing excess nutrients that potentially could be exported from the soil system via water mediated loss mechanisms such as runoff and/or leaching. The overall amounts, composition of the nutrients contained in animal manure, soil factors such as amount of clay and organic matter (OM), landscape and climate (Klausner et al., 1994) all contribute to the amount of P and N nutrients that can be exported from a field to a surface and/or subsurface water system. Application of cattle and/or hog manure at excessively high rates in excess of crop uptake could lead to soil buildup and accumulation of P and N nutrients that ultimately lead to nutrient export and loss from the field (Bernier et al., 2014).

Solid cattle manure can be high in both P and N content, and there is potential for various organic and inorganic forms of P and N in the soil originating from manure to be transported from the field with water, leading to adverse nutrient enrichment of surface and subsurface water bodies close to the land receiving the manure (Little et al., 2007). Phosphorus exists in organic and inorganic forms, both forms of which are transportable in solution and as particulates in water moving laterally and vertically in soils (Hay et al., 2006). Organic forms of P that dominate in many manure sources are important regulators of the bioavailability of soil P. However, the specific composition of soil P pools derived from manure, along with their turnover and mobility as affected by placement of manure are only recently being revealed (Kar et al., 2012). Forms of inorganic N in SCM such as ammonium N (NH_4-N) are available for plant uptake but can also be transported from the soil in run-off water (Powell et al., 2008) or transformed into highly mobile forms like nitrate. Ammonium N can be volatilized into ammonia gas. Once converted into NO_3-N in the nitrification process, leaching or denitrification can take place. (Arriaga et al., 2010).

Separation of manure P and soil P into various fractions using chemical extraction (fractionation) is one of the more commonly used methods to assess P forms and make inferences about the potential fate of accumulated P in the soil. In run-off or leachate water from soils, there are four categories of P forms generally identified including: 1) dissolved reactive P (soluble orthophosphate), 2) particulate reactive P (P fraction loosely adsorbed on clay, iron, aluminum or clay oxides), 3) dissolved unreactive P (primarily soluble organic P compounds) and 4) particulate unreactive P, in which the nature of the P compounds is strongly sorbed or precipitated P in mineral and humic acid complexes (Toor et al., 2006).

Consideration of the forms and distribution of P and N in Saskatchewan agricultural soils as affected by manure management practices such as manure application rate and placement is the first step in assessing the potential influence of the practice on nutrient migration. In particular, there is a need to relate manure and soil nutrient forms to nutrient distribution and mobility assessments. Factors affecting the distribution of P and N forms particularly in the upper 0-5 cm depth of the soil first need to be understood. Soil will retain a majority of P and N applied as animal manure that is not removed by the crop through transformations such as adsorption, precipitation and immobilization. Soil characteristics control the forms in which P is transported from the bulk soil to surface or underground water systems (Ulen and Snall, 2007). The P mobility is strongly controlled by its chemical and physical form (Hountin et al., 2000). Furthermore, soil P is associated with different size fractions (eg. clay) and losses from the soil can come through dissolution or detachment (particulate and colloidal P).

1.3 Movement of phosphorus and nitrogen in spring snowmelt

In western Canada, the primary water event which causes nutrient transport across and into the soil is related to the increase in temperature in March that signals the end of winter and the beginning of the spring annual snowmelt. Nutrients such as P and N can be exported in snowmelt surface water runoff and/or leaching in either dissolved or particulate form, leading to enhanced concentrations of these nutrients in water (Lorentz et al., 2008; Lui et al., 2014). Unlike some regions of North America where rainfall runoff can carry significant nutrient load in particulate form due to greater kinetic energy of raindrops creating particle detachment and erosion, snowmelt water runoff and/or leaching has lower kinetic energy, thus less erosive power and results in nutrient transport primarily in dissolved form (Jensen et al., 2000) over longer distances. Several studies in Manitoba and Alberta have reported that the amount of P exported in snowmelt runoff was directly correlated to the concentration of labile P in surface soils (Little et al., 2007; Salvano et al., 2009). Furthermore, where manure application was reduced, soil test P was reduced and the amount of P moved in runoff was also reduced. Recent studies in southwestern Saskatchewan have shown that N can be exported in spring snowmelt from pasture as dissolved NH_4 (Cade-Menun et al., 2013).

It is noted that in Western Canada, little information exists on nutrient transport by snowmelt water as affected by basic manure management practices like rates and methods of application of SCM cultivated fields. There is some recent information on P and N nutrient redistribution in a Saskatchewan hummocky landscape that received several fall applications of subsurface banded LHM. Priyashantha et al., (2007) reported that plant available P in these landscapes was greater in the footslope landscape positions, compared to the shoulder landscape position. The authors also reported that NO_3-N and NH_4-N concentrations in the surface soil in footslope positions was higher than the shoulder landscape position. Redistribution of manure nutrients downslope by water was believed to be a significant factor in these landscapes. (Priyashantha et al., 2007).

Water infiltration from snowmelt during the spring season depends on whether the soil is frozen or in a condition of thawing (Srinivasan et al., 2006). Continued freeze-thaw during the spring snowmelt could also create conditions for more runoff (i.e. when the soil surface is frozen) to conditions where more water will infiltrate into a thawing soil surface and leach downward in the soil profile. There are also conditions that could exist where soil is in a condition of thawing, yet saturated conditions in the unfrozen surface soil may allow little water infiltration (Ginting et al., 1998). Recently thawed fine textured soil will allow for only low water infiltration (Baker, 1972). Mid-winter melts can also lead to formation of a surface ice lens. runoff from snowmelt can occur in several ways. Water infiltration will be limited when the soil surface is frozen. Snowfall prior to freezing in the fall can serve to insulate the soil surface allowing more infiltration during the spring snowmelt and leading to saturation conditions, where excess water can move laterally. Finally, rainfall received during the spring snowmelt can lead to excess water being transported across a partially frozen soil surface (Srinivason et al., 2006). Studies have examined fall applied manure that was covered with snow, however, inconsistent impacts on run-off nutrient content have been reported. One study reported higher nutrient concentration in runoff (Young and Mutchler, 1976) while another study (Klausner et al., 1976), reported that when later spring season snowmelt occurred, nutrient export was lower. The timing and duration of the snowmelt period likely has a major impact on the amount of nutrient removed from the field during and immediately following the snowmelt.

1.4 Ph.D. Research Description

Limited information exists on the movement and export of inorganic P and N in cultivated soils receiving LHM and especially SCM applications in western Canada. There are an estimated 2.3 million cattle and calves in Saskatchewan (Saskatchewan Ministry of Agriculture 2015). New management practices for solid manures are being developed, including application through banding. Existing and new manure management practices require evaluation for their effect on P and N forms and distribution in soils, and in run-off and leaching water. My overarching hypothesis is that subsurface placement of manure in bands will increase the bioavailability but also the potential surface runoff and/or downward mobility of soil P and/or N nutrients. The objectives of this research are:

1. Evaluate new subsurface banding technology developed for SCM application on the crop yield and P and N crop uptake, compared to traditional application methodologies including broadcast alone and broadcast and incorporation.
2. Estimate the amount of soluble reactive P (SRP) and N transported offsite as affected by SCM and LHM rate and application methodology, using a novel approach in which intact soil slabs are removed from plots in short and long term SCM and LHM field studies in Saskatchewan and then have simulated snowmelt conditions applied in a controlled environment room.
3. Address the vertical nutrient transport potential through the soil profile by assessing the amount of OC, Total N, SRP and N that are transported through intact soil cores that were removed from SCM amended plots in the field and subjected to leaching water passed through the cores.

The studies that address these objectives will provide new information on agronomic and environmental implications of new versus existing manure management practices in western Canada that will be useful in the development of beneficial management practices and recommendations for manure application throughout the region.

1.5 Dissertation Arrangement

Following this introduction (Chapter 1) and subsequent literature review (Chapter 2), the research presented in this dissertation is a compilation of three manuscripts (Chapters 3-5) and an (Appendix A) detailing the work that was conducted to evaluate the effects of different methods and rates of SCM application and their effect on P and N bioavailability and mobility in the soil. Specifically, Chapter 3 covers the results of a three year study in east-central Saskatchewan that compared the crop yield, crop nutrient uptake and soil available P and N supply in plots treated with SCM using three methods of application (broadcast, broadcast and incorporated, novel subsurface banding) at three rates of application. This study provides a comprehensive understanding of the effects of SCM placement, specifically subsurface banding, on soil nutrient bioavailability and crop uptake and utilization of SCN nutrient. Chapter 4 investigates the effect that the three SCM application methodologies and two LHM application methodologies have on the transport and movement of P and N in simulated snowmelt run-off water, emphasizing both subsurface (thawing soil) and surface (frozen soil) transport. Chapter 5 deals with further investigation of transport of nutrients in water as affected by manure rate and placement by determining the amounts of P and N that are removed via vertical leaching from water that is applied to the surface of intact soil cores removed from SCM plots. This study enabled us to determine how the placement of SCM affects the export of nutrient from the surface via downward leaching (vertical transport) in the soil profile. Therefore, the studies involving snowmelt run-off in Chapter 4 (simulated early spring) and infiltrating percolating water in Chapter 5 (late spring and summer) cover the major water-related transport processes that manured soils in western Canada may be expected to experience. In the final chapter (Chapter 6), the results of each component of the work are brought together and integrated, with conclusions drawn and practical recommendations made for manure application best management practices. Also included in the dissertation is Appendix A, which is an assemblage of plot diagrams based on the treatment layout of the study.

2. LITERATURE REVIEW

2.1 Nutrient Benefits and Concerns Surrounding Land-Applied Animal Manures

Livestock operations produce large amounts of P and N in manure from animals that are fed plant materials and supplements containing these nutrients. In Canada, approximately 150 million tonnes of manure are produced annually which are applied to about 3.5 million hectares of land in 2005 (Statistics Canada, 2006). Benefits to crop production from the application of SCM and LHM to western Canadian soils to provide P and N nutrient have been well documented (Mooleki et al., 2004; Mooleki et al., 2002; Schoenau and Davis, 2006), along with other nutrients such as copper and zinc (Lipoth and Schoenau, 2007; Qian et al., 2003) if there is a limited supply of these micronutrients in the soil.

Phosphorus and N are essential elements for plant above-ground and below-ground tissue formation (Havlin et al., 2013). The application of animal manures has primarily been intended as a source of N for plant growth. Nitrogen is primarily utilized by the plant to form amino acids, proteins and nucleic acids. Additionally, N is utilized in the synthesis of chlorophyll which absorbs light energy for photosynthesis and aids in vegetative growth (Havlin et al., 2013). Accordingly, application of animal manure has been on an N-based approach, as this is the most widely utilized and most frequently deficient nutrient in crop production (Gburek et al., 2000). However, animal manures such as SCM can contain large amounts of P, depending on the source of the manure and its handling and processing in animal production facilities (Beauchamp, 1983; Eghball and Power, 1999; Mooleki et al., 2004).

Phosphorus is utilized by plants for energy storage and transport and typically is 0.1 to 0.5 % of the dry matter by weight in plant material (Havlin et al., 2013). In attempting to meet the N based requirements for plant growth, producers have in many instances applied manure to the point that there is an overabundance of P added to the field, that exceeds the ability of the crop to utilize the entire amount of manure P supplied (Sharpley et al., 2015). If the soil is not able to adequately adsorb the excess P supply via the mineral and organic components, the inorganic and organic manure P constituents that remain in the soil solution are prone to export off the field site via water runoff and/or subsurface leaching to surface and subsurface water bodies (Sharpley et al., 2015).

Phosphorus and N contained in animal manures such as SCM, can exist in both inorganic and organic forms. The application of LHM using subsurface banding methods and its positive effect on crop growth in east-central Saskatchewan has been documented by Mooleki et al. (2002). Mooleki et al. (2004) have also reported on studies conducted with SCM at rates of 400 kg N ha^{-1}, which resulted in increased plant N availability and crop yields during the year of application, and in subsequent years following application due to the slow mineralization of manure organic N to plant available inorganic N. The authors attributed the slow release of N from organic forms, and the low amount of inorganic N in SCM as also being responsible for low toxicity to the crop at high rates of application. They also reported that the timing of incorporation, whether immediately following SCM application or delayed by 24 h, had no effect on crop yield or on soil N content. A non-nutrient benefit of solid manures is the significant addition of organic matter directly to the soil that can improve important soil physical properties like structure and tilth of the soil (Grevers et al., 2010).

With the nutrient and soil organic matter building benefits associated with manure, intensive livestock operations also bring concerns about the consequences of improper application of animal manure (Lague et al., 2006; Sanderson and Jones, 1997). Livestock manure is recognized as a source of organic material (OM) and important plant nutrients but there always exists concerns about erosion or leaching events removing these nutrients and transporting them off-site to surface and/or subsurface water bodies (Eghball and Power, 1994). Furthermore, catastrophic events such as flooding can impact the solubility and mobility of P in soils (Scalenghe et al., 2014). The rate of decomposition of the manure organic matter constituents such as fecal matter and bedding into soluble, potentially mobile inorganic nutrient ions can vary depending on the manure type, such as LHM or SCM. The C:N and C:P ratio of the manure, the climate zone the soil is located in and the conditions in the soil upon which the manure is being placed (e.g. temperature, moisture) also influence the degree to which manure nutrients are rendered reactive and potentially mobile (Klausner et al., 1994). Beauchamp (1983) and Pang and Letey (2000) have reported that soil N availability in the year of SCM application is low, due to most of the SCM N being in an organic form, which takes time to be converted into a plant available inorganic form, especially if the C:N ratio is high (Qian and Schoenau, 2002). Thus, if the rate of SCM is increased to meet the immediate N requirements of the crop due to low short-term availability of the N, this can rapidly lead to an excess in soil P (Chang et al., 1991) contributing to run-off and leaching losses.

2.2 Manure Application Method and Nutrient Retention in Soils

Current SCM application technology is limited in that the rate and uniformity of manure application is often not controlled effectively (Landry et al., 2005). Non-uniform application of SCM can lead to zones in agricultural fields where too little or no SCM is placed while other areas in the field have zones where the manure is over-applied. Application technologies generally fit one of several types: 1) broadcast alone, with no incorporation at time of application; 2) broadcast with incorporation following spreading, 3) application through an irrigation pivot or 4) subsurface injection or banding (Schoenau and Davis, 2006). Timing of animal manure application can occur during spring pre-seeding, fall post-harvest or winter application of manure. The method of application and/or timing can profoundly influence the nature and extent to which nutrients are exported from a field. For example, N loss through volatilization by surface placement has been documented by several researchers (Sanderson and Jones, 1997; Zhu et al., 1997). Mooleki et al. (2002) reported on the positive crop yield obtained when subsurface banding LHM compared to broadcast and incorporation, and the increase in N use efficiency obtained from subsurface banding application method versus broadcast and incorporation.

There is a tendency to land apply animal manure at high rates based on desire to simply dispose of the product, without consideration for the nutrient content or makeup of the manure in relation to crop needs. This, in turn, can lead to over application of some nutrients contained in the manure. Consideration of nutrient balance in manure is important, and how application method may affect this. Large losses of N during application but retention of P will aggravate issues with an imbalance of too little N relative to P in relation to crop requirements. On the other hand, retention of both N and P may ultimately lead to over-application of both, and increases in soil nitrate-N (NO_3-N) concentration to the point at which excessive amounts can be leached downward in the root zone to potentially contaminate subsurface water (Dauden et al., 2004). The application of animal manure at N-based rates can result in over-application of other nutrients such as P (Mooleki et al., 2004), which if transported off a field site can lead to excessive amounts of P in runoff (Pote et al., 1996; Wang et al., 2010) and in subsurface water (Simard et al., 2000; Sims et al., 1996) which increases the risk of eutrophication (Sharpley et al., 1994).

Current SCM application technology is limited in that the rate and uniformity of manure application is not controlled effectively (Schoenau, 2013). Solid animal manures have been traditionally applied to agricultural fields using a box- type spreading mechanism that can limit solid manure spread uniformity, largely through limitations in beater design and also wear over time. The recent move from horizontal to vertical beaters has improved the distribution to a certain extent based on personal observations. Such units also typically provide only limited control of the rate of application, mainly by altering travel speed (Lague et al., 2006). The lack of uniform application in surface applied SCM and the potential for excessive application rates of the P and N in zones could lead to toxicity risks for the crop and also increase the potential for off–field movement and site contamination of surface and subsurface water bodies. This is because the zone of over-application may become saturated in terms of its sorption capacity for the nutrient ion. Subsurface banded manure can also create zones of high nutrient concentration (Kovar et al., 2011). Repeated manure applications can result in P accumulation in soil, and this accumulation can partially or completely saturate soil adsorption sites, depending on OM and clay content (Qian et al., 1994). Phosphorus that is not utilized by the crop or adsorbed onto OM or clay mineral components is considered mobile, susceptible to run-off and leaching losses (Eghball et al., 1996) and can be more readily moved all the way to surface and subsurface water bodies (Schroeder et al., 2004; Vadas et al., 2005).

2.3 Manure Application Rate and Application Methodology on Nutrient Transport in Water

Many studies examining transport of nutrients in surface run-off have emphasized the effect of application rate of animal manure in comparison to an unamended control (Eghball et al., 2002; Kleinman et al., 2002; Kleinman et al., 2004; Mueller et al., 1984). A few researchers have also reported on the effect that manure application methodologies have on P transport in run-off (Volf et al., 2007) (Eghball and Gilley, 1999; Kleinman et al., 2002; Mueller et al., 1984). For example, Kleinman et al. (2002) reported that with manure incorporation into soil, there was a decrease in concentration of P in run-off and greater adsorption of P to soil constituents. Depending on soil and climatic conditions, field management and cropping history, excessive manure application rates can result in high NO_3-N accumulation (Zebarth et al., 1998). Rates of application of SCM containing amounts of P in excess of crop P uptake capacity can increase soil extractable P levels and thereby increase the risk of export off a field site through runoff (Reddy et al., 1999;

Sharpley et al., 1994; Withers et al., 2001). Volf et al. (2007) reported that plots amended with fresh SCM that was incorporated had run-off P that was not significantly different from plots that had received SCM one year prior. Sharpley et al. (2015) reported that N-based manure applications have led to an increase in soil P levels that are in excess of crop requirements. This is especially noted for cattle manure, as it is inherently high in P relative to N (low N:P ratio) (Schoenau and Davis, 2006; Stumborg et al., 2007). Studies have reported that when cattle feedlot manure is applied on a P-based crop requirement, there is a tendency for reduced P in run-off (Eghball and Gilley, 1999; Eghball and Power, 1999) and several researchers have reported on the direct relationship between manure P application rate, soil P levels and P in run-off (Daniel et al., 1994; Sharpley and Rekolainen, 1997).

Pote et al. (1996), Schroeder et al. (2004), Lemunyon and Gilbert (1993) and Heathwaite (1997) reported that many variables such as amount of clay mineral particles and subsequently the adsorption capacity, along with moisture content, calcium carbonate content, climate, landscape slope and management practices all affected the amount of P being exported in run-off. Ingram and Woolhiser (1980) suggested that rainfall event intensity, run-off energy and landscape slope affected the degree of interaction between nutrients in the soil and nutrients transported in run-off. Little et al. (2005) stated that tillage could also reduce run-off nutrient transport by redistributing nutrients deeper in a soil profile, while flooding of the soil can increase P solubility and accelerate P loss (Kroger et al., 2012). The accumulation of nutrients from repeated animal manure applications can increase or concentrate nutrient amounts near or at the soil surface (Seta et al., 1993). Eghball and Gilley (1999) used a rainfall simulator to measure P and N in run-off from plots amended with composted and feedlot manure. They reported that there was little amendment type effect on dissolved P or total N. Qu et al. (1999), reported that in plots amended with fresh and composted dairy cattle manure, total N concentrations in the run-off water was greater in fresh dairy manure compared to composted dairy manure. In general, over-application of SCM, and prolonged yearly applications of SCM can lead to non-point source contamination of surface and sub-surface water bodies where excess NO_3-N and P are not taken up by the crop or adsorbed onto soil mineral and organic adsorption sites.

Prior knowledge on the behavior of P in soil was that it was immobile in soil (Haygarth and Jarvis, 1999). However, it is now known that P applied in fertilizer or animal manure can be transported to a certain extent through overland run-off or subsurface leaching (Hart et al., 2004).

Soils that have lower amounts of OM or clay increases the chances that P can be transported via run-off or downward leaching through preferential flow pathways several centimeters or more through the soil (Sharpley et al., 1998; Sharpley and Rekolainen, 1997). Phosphorus transport in water from run-off or leaching can depend on the manure type being applied to the soil, the timing (whether it's a fall or spring application) (Edwards and Daniel, 1993; Sharpley, 1997), the rate of application and the methodology used to apply the manure (Withers et al., 2001). Nonpoint source contamination of surface and subsurface water bodies from P and N released from animal manure application is of a great concern. Problems with eutrophication, where algae growth is increased due to nutrient enrichment of water bodies can cause problems for aquatic and human health (Kumaragamage et al., 2011). The amount of P that is transported by water from run-off or leaching can be variable in land receiving animal manure (Sharpley et al., 1998). This literature review has revealed that little information exists on the amount of P transport in run-off and leachate water from land receiving SCM through subsurface banding technology.

2.3 Nutrient Movement Associated With Snowmelt

In western Canada, spring snowmelt is the primary water movement event and P and N nutrients can be transported in dissolved and particulate forms, leading to increased nutrient concentrations in water that reached subsurface and/or surface water bodies (Jensen et al., 2000). The P dissolved in snowmelt run-off water can be transported much longer distances throughout the landscape than particulate forms. Tiessen et al. (2010) reported that in examining snowmelt runoff from two Manitoba watersheds, snowmelt runoff accounted for between 80-90 % of total annual runoff. Snowmelt water has less soil erosive capability, due to the lower kinetic energy associated with this type of water movement, thus more P and N nutrient movement can occur in a dissolved form (Cade-Menun et al., 2013) and can be exported over longer distances as snowmelt water travels longer distances over fields from higher slope areas (Priyashantha et al., 2007) to lower slope positions. Tiessen et al. (2010) reported that the majority of particulate and dissolved nutrient export from two Manitoba watersheds occurred during the spring snowmelt runoff. Therefore, the work on P transport in run-off described in this thesis attempts to simulate the transport that may occur in dissolved form in spring snowmelt water as affected by manure management practices.

Annually cropped agricultural fields have, in some cases, evolved from serving as an adsorption zone for nutrients such as P and N to a potential transport zone if the planted crop is unable to use all the applied nutrients in a single growing season (Liu et al., 2013; Sharpley and Wang, 2014). Therefore, with over-application of manure and improper placement, soils can turn from a sink to a source of nutrient ions like phosphate to be moved into adjacent water. Phosphorus has been reported to move from agricultural soil by leaching to surface and subsurface water bodies (Eghball et al., 1996; Flaten et al., 2003). The transport of P occurs first through a loading process whereby P is released to soil solution from the solid phase which can consist of P adsorbed to soil mineral and organic colloid surfaces. A transport function occurs where moving water then translocates the P by movement across the surface in run-off or through the soil horizontally or vertically with percolating water (leaching) (Jensen et al., 2000). Transport of P through the soil profile is enhanced by preferential flow through soil cracks and macropores and low abundance of soil adsorption sites (Beauchemin et al., 1996; Culley et al., 1983).

Previous research conducted in western Canada has reported that soil P losses from spring snowmelt can be greater than what occurs due to run-off from rainfall (Chanasyk and Woytowich, 1987; Van Vliet and Hall, 1991). Water infiltration during the snowmelt period can depend on whether the soil is in a frozen state, thawing condition (Srinivason et al., 2006) or a continuous cycle of freeze and thaw, which can exacerbate conditions more favorable to runoff than infiltration. The timing and duration of spring snowmelt can also have a major impact on nutrient exported in runoff and/or in downward moving leachate. Several studies reported conflicting results on the amount of nutrient transport in meltwater depending on whether snowmelt was an early or later spring season event (Klausner et al., 1976; Young and Mutchler, 1976). Furthermore, snow melting over frozen soil, when spring temperatures begin to increase, can release a large amount of water that can either run off the field site, or else as the soil begins to thaw, begin to percolate downward in the soil profile (Li et al., 2011). Snowmelt run-off can exceed rainfall run-off, due to the soil being frozen thus limiting water infiltration (Granger et al., 1984; Hansen et al., 2000; Young and Mutchler, 1976). The late winter, early spring period in which snowmelt occurs (e.g. mid-March in the southern prairies) can favor more saturated conditions occurring near the soil surface that can increase P mobility (Bechmann et al., 2005; Little et al., 2007; Ontkean et al., 2005).

Snowmelt run-off has less erosive ability compared to rainfall run-off as the kinetic energy generated by the force of the raindrops contacting the soil surface can cause more soil particle detachment and movement thus removing more particulate forms of nutrients with SOM particles (Li et al., 2011). Large amounts of dissolved forms of nutrients can be carried off the field with run-off occurring from large volumes of snowmelt in western Canada, especially when infiltration rates are reduced due to soil surfaces that are frozen in the earlier portion of the spring period (Chanasyk and Woytowich, 1987; McConkey et al., 1997; Van Vliet and Hall, 1991). Glozier et al. (2006) reported that approximately two-thirds of the P and N removal due to snowmelt run-off in southern Manitoba occurred in a dissolved form. Little et al. (2007) reported that in Alberta, over 90 % of the P removed by spring snowmelt was in a dissolved form. Fleming and Fraser (2000) have reported that frozen bare soils do not allow infiltration of dissolved P and N. The work described in this thesis emphasizes dissolved ionic forms of P and N that are transported in water, owing to the identified importance of this fraction in Western Canada.

2.4 Synopsis and Relationship to Thesis Research Work

When animal manure is added to the soil, there is a P and N nutrient input to the soil. Some of the inorganic P and N may be immediately immobilized into organic forms and retained, or held by adsorption to soil mineral and OM particles. Some nutrient ions that remain in soil solution or that are mobilized through mineralization or desorption can be exported from the soil by water moving laterally or vertically through the soil. A portion of the nutrient will invariably remain in a labile or plant available form at the end of the season after harvest. The relationships between applied manure nutrients, their potential fate, and the specific components of the research work described in this thesis are shown in Fig 2.1. A significant aspect contributing to the novelty of the thesis work conducted is determining how new subsurface banding technology for solid manure application affects plant yield and nutrient content, soil supply of P and N, and the export of dissolved P and N via snowmelt run-off and leaching. In Saskatchewan, the major water movement period occurs during early spring snow melt when melt water moves across the soil surface and through the upper soil surface, and can carry nutrients in the flow. Thus the application of SCM and LHM through subsurface banding could have a major impact on P and N movement off a field compared to surface application. This is examined in this thesis through the development of a novel method in which intact soil slabs are removed from plots that have been treated with subsurface banded SCM and LHM, snow cover is applied and subsequently allowed to melt under controlled conditions to measure the amounts of P and N that are being transported off a field site from run-off and leachate (Fig. 2.1). To address the influence of subsurface banding on nutrient transport with downward percolating water such as from snowmelt or precipitation, intact soil cores were collected and leached (Fig. 2.1), with the leachate water collected and analyzed for soluble ionic P and N forms. Because a defined surface area is present from which the run-off or leaching occurs, the nutrient exports are calculated on a kg per ha (area basis).

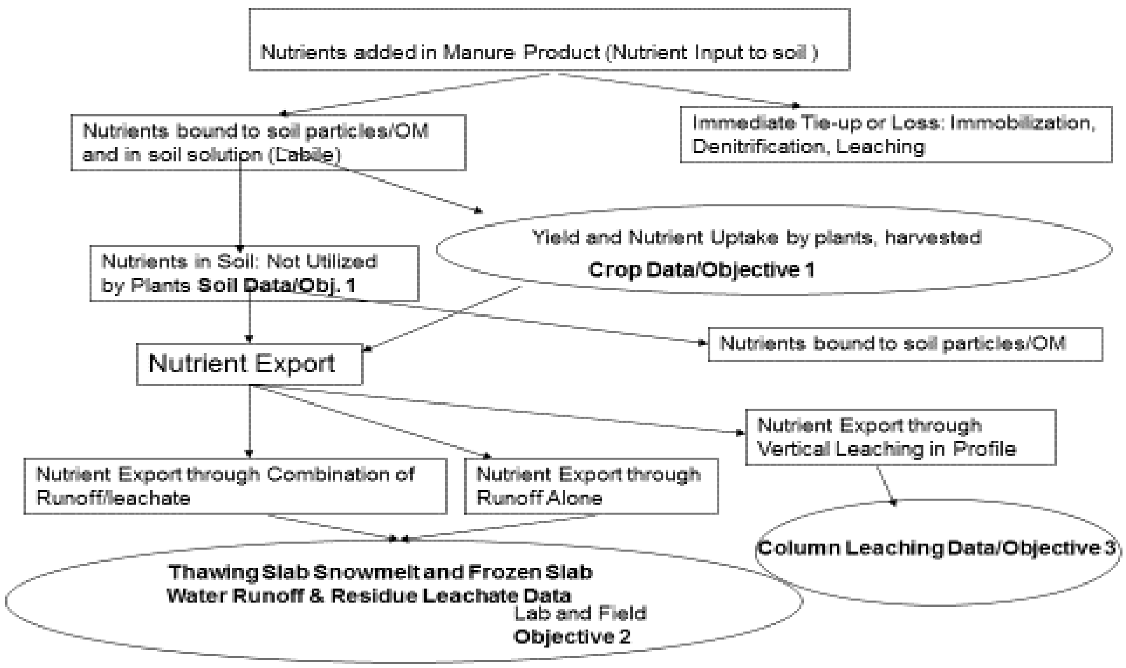

Fig. 2.1. Schematic diagram outlining the study of phosphorus and nitrogen nutrient export in solid cattle manure and liquid hog manure amended soil.

Overall, a review of the literature reveals that a great deal of past research work has been conducted examining the effect of manure application rate on crop response and nutrient loss. Some work has also examined the effect of placement. However, there is little information that links together manure placement effects, particularly new band placement technologies, for both agronomic responses and nutrient transport potential. While crop response and soil nutrient forms and amounts can be assessed reliably in replicated small plot studies, run-off assessments have traditionally been made in separate large scale catchment basin or watershed scale studies. There is a need to meld together replicated randomized block studies of agronomic effects with capacity to study run-off potential at the same time. The research described in the next three chapters of this thesis helps to address this gap.

3. EFFECT OF SOLID CATTLE MANURE RATE OF APPLICATION AND MANURE PLACEMENT ON CROP YIELD AND SOIL NUTRIENTS IN A BLACK CHERNOZEM IN EAST-CENTRAL SASKATCHEWAN

3.1 Preface

The application of solid cattle manure (SCM) to agricultural fields is a long practiced method of adding organic matter and recycling nutrients in agroecosystems. Solid cattle manure has traditionally been broadcast applied to the entire field with manure spreaders at rates that are often unknown to the applicator and with equipment that applies the SCM non-uniformly. Despite the benefits of SCM in adding nutrients to the soil, the inability to control the rate and uniformity of application can lead to potential undesirable agronomic and environmental consequences. SCM may be applied using surface broadcast alone and broadcasting followed by incorporation with existing equipment. New technology is also being developed to apply solid manure in sub-surface bands. Assessing crop yield, soil and crop residue nutrients as affected by method of SCM application in prairie soils, including new placement methods, will aid in understanding the effects on soil nutrient availability and crop yield. This chapter covers the agronomic implications of application of different rates and placement methods of SCM in an oat-canola rotation at a site in east central Saskatchewan over a three year period. Subsequent chapters then cover the implications of manure amendment on nutrient export in simulated run-off and leaching. A paper has been published by authors: Landry, H., King, T, Schoenau, J.J., Lague, C. and J.M. Agnew. 2011. Development and evaluation of subsurface application technology for solid organic fertilizers. Applied Engineering in Agriculture (Vol. 27: 533-549). This paper incorporates a portion of the agronomic work researched in this chapter.

3.2 Abstract

Assessing and quantifying crop and soil impacts of different rates and application methods of solid cattle manure (SCM) in an annually cropped system will allow the adoption of appropriate manure management practices that will enhance the agronomic benefit of the manure. The objective of this study was to evaluate the effect of broadcast alone, broadcast and incorporated, and subsurface banding of SCM in an oat-canola rotation in a Black Chernozem soil located in east-central Saskatchewan. Manure application increased yields over the non-manured, unfertilized controls, but the effect of increasing rate and placement methods consisting of broadcast alone, broadcast and incorporated and subsurface banded, was usually not significant. Only the subsurface banded 20.2, 40.4 and 60.6 t ha^{-1} SCM treatments increased canola grain yields compared to the broadcast alone and broadcast and incorporated SCM treatments at these three rates in 2008, and only when combined with nitrogen (N) urea fertilizer at a rate of 78 kg N ha^{-1}. This was attributed to enhanced supplies of available phosphorus (P) from the manure that, when limitations on N were removed by urea fertilization, resulted in greater yield. Soil supply rates of orthophosphate-P in the surface soil, as measured by PRS™ resin membrane probe, tended to increase through the 2009 growing season in all three SCM 60 t ha^{-1} application treatments. Soil nitrate-nitrogen (NO_3-N) supply peaked for all three SCM 60 t ha^{-1} application treatments approximately six weeks after the 2009 oat crop was seeded, then diminished during the mid and late July 2009 sampling periods. However, there was no significant impact ($P \leq 0.10$) of SCM placement method on supply rates of phosphate and nitrate measured in the surface soil in the field. The release of P and N from collected canola crop residues in 2008 was also measured. The canola residue total P and N content was decreased when canola crop residues were immersed in water and frozen. In the case of P, concentrations were reduced nearly two-fold, indicating an important role of leaching in removing and recycling P from crop residues after harvest. However, manure application rate and placement method had no significant influence on crop residue P and N content or release of nutrient from residue. Overall, the rate of application of SCM appears to have a more profound effect on soil and plant nutrient concentrations and yield, especially P, than the method of SCM placement.

3.3 Introduction

The agronomic benefits of application of liquid hog manure (LHM) in a subsurface band versus surface application are well established (Mooleki et al., 2002). Feeding of animals and the land application of animal manure recycles the nutrients removed from the soil by plants and reduces the need for commercial fertilizer to fulfill future crop nutrient requirements (Jungnitsch et al., 2011). Current application technology available for applying solid cattle manure (SCM), however, is limited in that the rate and uniformity of manure application is not controlled very effectively (Landry et al., 2005). Non-uniformity in surface application of SCM as a result of poor spreading can lead to zones where little or no SCM is placed, while other areas in the field experience over application of manure. Furthermore, surface broadcast applications of some manures are well known to promote potential additional losses of N from volatile ammonia escape, especially under warm and windy conditions (Havlin et al., 2014). Surface placement without incorporation can also strand nutrients near the surface of the soil, reducing their availability for root uptake. Incorporation of solid manure following spreading is commonly practiced in the northern Great Plains (Schoenau and Davis, 2006) to help retain manure nutrients, but is not compatible with the no-till system common in western Canada and is associated with extra cost and time required for one or more tillage operations to conduct the incorporation. Prototype sub-surface banding equipment is available that can improve the uniformity of application by putting manure in uniform bands below the surface. However, the agronomic benefits of such an approach to application have not been evaluated.

It was hypothesized that the crop yield and nutrient availability would differ among various SCM application rates and placement methods. Therefore, the objective of the work described in this chapter was to evaluate the effect of application of SCM applied annually at three different rates using broadcast only, broadcast and incorporated, and a novel subsurface banded application method. Effects on crop yield, soil and crop and residue nutrients were evaluated in a three year experiment conducted on a Black Chernozem soil in east-central Saskatchewan near Dixon, SK. The crop yield, phosphorus and nitrogen uptake in an oat-canola rotation was measured each year, and a comparison of the effects of the treatments on soil nutrient supply rate in the surface soil and the nutrient content and release from canola crop residue was made.

3.4 Materials and Methods

3.4.1 Site description

The SCM injection study at Dixon, SK was established in the spring of 2007 before spring seeding operations commenced, with the first applications of SCM (Appendix A). The experiments were initiated on the southern half of a farm field (N 52.196193; W 105.232150) owned by Mr. Collin Ford. This field is located approximately 6.5 km west of the town of Humboldt; adjacent to Saskatchewan Provincial Highway #5, within the Rural Municipality of Humboldt (Figure 3.1). The soil at this site belongs to the Cudworth Association and is a Black Chernozemic soil formed in calcareous, silty, lacustrine parent materials and possessing a loam surface texture (Saskatchewan Soil Survey, 1989). The soil at the Dixon field site occurs on a gently sloping land surface with few limitations that hinder agricultural activity. Identified limitations include insufficient moisture holding capacity and some salinity, which covers 10-20% of the landscape, occurring mostly in sloughs and low lying areas (Saskatchewan Soil Survey, 1989). This field site is only slightly stony and has a low susceptibility to wind and water erosion (Saskatchewan Soil Survey, 1989). Crops grown on the Dixon site were oats (*Avena sativa*) in 2007 and 2009 and canola (*Brassica napis*) in 2008.

Fig. 3.1. Photograph of a portion of the Dixon solid cattle manure application site, taken on May 10, 2007 after flagging to mark plot locations for treatment application, and spring and fall crop and soil sampling.

3.4.2 General experimental setup

The SCM field trial was set up as a randomized complete block design (four treatment replicates) with plots laid out in April of 2007. Within each block, rate and method of application treatments were randomized. Four blocks of treatments were used with alleyways between the blocks to allow for application equipment turning and access to the plots. The size of each plot was 3.05 by 6.09 m. There were two control plots for the SCM trial at Dixon, the first consisting of no manure or fertilizer being applied and no disturbance of the soil. The second control plot had no manure or fertilizer applied but with disturbance of the soil using the coulter openers of the SCM injector machine. Solid cattle manure was applied every spring before seeding over the three years of the study (2007, 2008 and 2009) using four application procedures: 1) broadcast application; where SCM is applied on the soil surface without incorporation, 2) broadcast and incorporated; where SCM is applied on the soil surface and subsequently incorporated using a disk, 3) subsurface banding; where SCM is subsurface banded using the PAMI Solid Cattle Manure Injector Machine (Fig. 3.2) in six subsurface trenches using 30 cm coulter openers spaced 30 cm apart, applying SCM product 10-13 cm in depth with 45 cm closing wheels covering the exposed injection trench with soil, and 4) subsurface banding of SCM with commercial urea fertilizer (46-0-0; at a rate of 78 kg N ha^{-1}) banded into the soil using a small plot drill prior to the injection of the SCM.

Fig. 3.2. Prototype Prairie Agricultural Machinery Institute-University of Saskatchewan solid cattle manure injector in field.

Treatment 4 was included as a treatment to reflect the low availability of N in SCM in the year of application (Mooleki et al., 2004) that may be compensated for by the addition of supplemental commercial N fertilizer.

The lowest rate of SCM being applied (1X) was equal to 100 kg total N ha^{-1}, at a rate of manure product of 20.2 t ha^{-1}, and may be considered a typical agronomic rate in line with the amount of N that would be recommended as fertilizer manure to meet a crop requirement. Higher rates of SCM (2X = 40.4 t ha^{-1}, 3X = 60.6 t ha^{-1}) were considered to be double and triple the recommended agronomic rates of N fertilizer application for an application to be made every year. The SCM injection trials consisted of 14 treatments (Table 3.1) that were replicated in four blocks, arranged in a west to east direction (Appendix A) and were laid down in a randomized pattern in the spring of 2007 before the producer commenced seeding operations. The 1X refers to the recommended rate (100 kg N ha^{-1} yr^{-1}) of SCM applied annually. The 2X and 3X indicate double and triple the recommended rate of SCM applied annually, respectively. For the SCM subsurface banded treatment with urea fertilizer, the 1X, 2X and 3X rate corresponds to 20.2, 40.4 and 60.6 t ha^{-1} rate of manure, with the same urea fertilizer rate (78 kg N ha^{-1}).

3.4.3 Manure characteristics

The SCM applied in the field trial at Dixon was obtained from the Poundmaker Feedlot, which is located approximately 8 km east of the town of Lanigan, SK. The manure that was applied had been removed from pens and stockpiled for approximately one year. The manure was applied to the appropriate plots using the PAMI SCM Machine. Broadcast applications were made by removing the disc opener component of the machine and allowing the manure to exit the box across the soil surface. The broadcast and incorporation application was broadcast followed by immediate incorporation to a depth of 10 cm using a 6 m tandem disc pulled by a John Deere 7800 140 hp front wheel assist tractor. Application rates of the SCM are listed in Table 3.1.

The SCM treatments were applied prior to seeding of the Dixon site on June 12, 2007 for the 2007 crop year, on May 10, 2008 for the 2008 crop year and on May 19, 2009 for the 2009 crop year. Manure sub-samples for the SCM applications for each year of application were obtained from the application equipment at the time of treatment application in the field plots.

Table 3.1. Targeted nitrogen application rate treatments in the solid cattle manure rate/placement study (2007-2009) at Dixon, Saskatchewan.

Treatment[†] (t ha^{-1})	Sequence	N rate (kg N ha^{-1})	Application method
0	control	0	with no incorporation
0	control-disturbed	0	with no incorporation, but disturbance
20.2	1X[‡]	100	
40.4	2X	200	cattle manure broadcast only
60.6	3X	300	
20.2	1X	100	
40.4	2X	200	cattle manure broadcast and incorporated
60.6	3X	300	
20.2	1X	100	
40.4	2X	200	cattle manure subsurface injected
60.6	3X	300	
20.2	1X+U[§]	100	
40.4	2X+U	200	cattle manure subsurface injected + urea[¶]
60.6	3X+U	300	
urea fertilizer	U	78	banded urea 46-0-0 fertilizer

[†] Application rate based on wet weight
[‡] The sequence, 1X for example, refers to the rate of manure application in the crop year ongoing annually since 2007
[§] Urea fertilizer
[¶] The rate of urea fertilizer application plus the corresponding SCM injection rate in the crop year ongoing annually since 2007

Samples were stored in 10 L plastic containers and placed into frozen (-20 $^{\circ}$C) storage, prior to analysis for their constituent nutrients. For the SCM samples, individual containers were removed from frozen storage and thawed at room temperature and sampled for nutrient content analysis. After thawing, samples were opened in the laboratory fumehood and stirred to mix the contents. Total N and P were measured by sulfuric acid peroxide digestion and soluble ammonium and phosphate by water extraction (Thomas et al., 1967). The concentrations of N and P in the manure used in the three years, along with calculated application rates are shown in Table 3.2. The targeted N rate was 100 kg N ha^{-1}. Soluble, available P in the manure made up a larger proportion of the total P content. Immediately available N (inorganic ammonium-nitrogen) (NH_4-N) constituted a small portion of the manure total N content. Overall, nearly all of the N in the cattle manure was in the organic form, with very low concentrations of NH_4-N (Table 3.2).

Table 3.2. 2007, 2008 and 2009 solid cattle manure composition.

Application year	Total N	NH_4-N	Total P	Soluble P	Moisture (%)
	------------------µg nutrient g^{-1} wet manure----------------				(O.D. basis)
2007	4304	16	2439	120	191
2008	2997	2.5	2518	193	35
2009	9350	3	3560	205	27

	Total N	NH_4-N	Total P	Soluble P
	Application rates of nutrient. Rate: 20 t ha^{-1} (1X)			
	--------------------------------kg ha^{-1} ------------------------------			
2007	100	0.84	56	4
2008	60	0.05	50	4
2009	187	0.06	71	4

† Moisture percentage on an oven dry (O.D.) basis

3.4.4 Field operations and plant and soil sampling and analysis

In 2007 and 2009, oats (*Avena sativa,* var Dancer) were seeded (June 18, 2007; May 26, 2009) at a rate of 105 kg ha^{-1} using a plot seeder with a row spacing of 20 cm. On the day before seeding, plots received an application of glyphosate to control weeds at a rate of 0.8 L active ingredient ha^{-1}. A post emergent application of bromoxnil-MCPA was made to control broadleaf weeds in early July. In 2008, canola (*Brassica napus,* var Clearfield) was seeded on May 18, 2008 at a rate of 5.5 kg ha^{-1}. An application of imazamox/imazethapyr herbicide to control grassy and broadleaf weeds was made on June 10, 2008.

Plant samples were collected from the plots in the last week of August just prior to the producer swathing the oat (2007), canola (2008) and oat (2009) crop. Using duplicate 1.0 m^2 quadrats, plant samples were taken by cutting the stalks approximately 5 cm above the soil surface, and returned to the lab where they were dried at 35 °C, weighed (total biomass weight was recorded), threshed and cleaned (separated into grain and straw components). The grain and straw samples were ground using a Wiley mill and a 0.25 g sample of ground grain or straw was digested using a sulfuric acid-peroxide digestion technique to determine total P and total N concentration (Thomas et al., 1967). Soil samples (0-15 cm, 15-30 cm) were collected from the site in the first week of September of 2007, 2008 and 2009 following harvesting operations and were obtained using a truck-mounted mechanical soil coring unit. Four separate cores were taken from each plot, and the samples from each core were bulked according to the sampled depth. Samples were extracted for available NO_3-N and NH_4-N using 2MKCl (Keeney and Nelson, 1982) and available P using modified Kelowna extracting solution (Qian et al., 1994) followed by colorimetric ion analysis using a Technicon automated colorimetry system. Soil pH and electrical conductivity (EC) were measured on a 2:1 (water:soil) suspension using a Horiba meter, and organic carbon (OC) was measured using dry combustion method at 840 ^{o}C (Wang and Anderson, 1998) on a Leco CR-12 Carbonator.

3.4.5 Measurement of surface soil phosphorus and nitrogen supply rates

In the 2009 season, Plant Root Simulator (PRS™) anion exchange resin membrane probes were placed into control-disturbed, urea fertilizer, and 60 t ha^{-1} SCM broadcast alone, broadcast and incorporated and subsurface banded treatment plots over the growing season from May to August. The first placement was made on May 22, 2009, approximately 1-2 days after seeding operations had been completed in the field. Before the probes were inserted into the soil each time in the field, deionized water was added to the surface of the soil (about 50 mL) to a small area (10 x 10 cm) to bring the surface of the soil to field capacity to promote exchange of ions between soil and the membrane surface and provide a consistent moisture content over the measurement periods (Qian and Schoenau, 2002). The PRS™ probes were inserted to encompass a depth of soil extending from the surface to 1 cm below the soil surface, and the soil was re-packed to obtain good soil to probe contact and left *in situ* for 2 h, at which time the probes were removed, bagged, labeled and transported immediately back to the University of Saskatchewan for storage and analysis (Fig. 3.3).

This procedure was repeated every two weeks during the growing season on June 3, June 17, June 30, July 14 and July 28, 2009. After harvest operations had been completed, another set of anion PRS™ probes were placed in the designated plots on October 16, 2009. Upon arrival at the lab, the probes were washed using distilled water to remove excess soil particles and then eluted using 0.5 *M* HCl (BDH, reagent grade). The probe eluent was then placed in 4 $^{\circ}$C storage until analysis for the colorimetric determination of NO_3-N and PO_4–P using a Technicon™ automated colorimetry analyzer.

Fig. 3.3. Photograph depicting usage of PRS™ probes to measure soil P and N supply.

3.4.6 Determination of phosphorus and nitrogen content and release from crop residue

Crop residues comprised of standing stalks and stalks spread by harvesting operations left on the soil surface after a combine harvester had passed through the plots were collected in October of 2008 from the 60.6 t ha^{-1} SCM rate placement treatment plots using one square meter quadrats that were randomly placed within each plot area. The crop residues collected consisted largely of canola residue from the 2008 crop but also some oat straw residue from 2007. The plant residue samples that were collected were immediately frozen and stored at -20 ˚C. The samples were then thawed, dried and the biomass was weighed. A sample of the residue was retained, dried at 35 °C, and then ground and digested for total N and total P concentration as described for harvested plant material in section 3.4.3. Each residue sample was then divided into two separate portions. One portion was set aside for snow melt leaching and one portion was set aside for water leaching. The crop residues for water leaching were first placed in a plastic bag. Then 3.75 L of water was added (equivalent to 7.5 cm of rainwater) and allowed to soak for 48 hours. After this, the residues were placed in frozen storage at -20 ˚C for 72 h to simulate a freeze-thaw (Fig. 3.4). After 72 h of frozen conditions, the crop residue samples in the plastic bags were cut open and the contents placed into plastic collection buckets equipped with plastic colanders to capture the thawing leachate water. Fiberglass screen (mesh size 1.40 x 1.10 mm) was placed between the frozen residue and the colander to prevent residue from mixing with the leachate. After thawing, the residues were then dried at 35 ^{o}C and ground and digested to determine total N and P concentration as described previously.

Fig. 3.4. Photograph depicting frozen crop residues after soaking in water for 48 h and then frozen for 72 h.

3.4.6 Statistical analysis

The three year SCM study was analyzed as a randomized complete block design, with four replications for crop grain and straw yield and nutrient uptake, soil P and N supply rates, and plant residue total P and total N content. Sample data was analyzed for normality and equality of variances using the univariate procedure and log transformed where necessary. Statistical comparisons were conducted using the general linear model procedure using a least significant difference (LSD,$P \leq 0.10$) for means comparison, calculated with SAS Proc GLM (SAS version 9.0, 2008).

3.5 Results and Discussion

3.5.1 2007 Crop year: Rate effects on yield

In 2007, oats were grown at the Dixon site. There was a significant (*$P \leq 0.10$*) yield response of oats to the addition of SCM when comparing the control treatments to the three SCM application treatments and the urea fertilizer (Table 3.3). However, there were no significant differences in crop yield between the broadcast alone, broadcast and incorporated and subsurface banded SCM treatments. Oat grain yield was similar in the three SCM treatment broadcast alone, broadcast and incorporated and subsurface banded SCM treatments, averaging around 4500 kg ha^{-1}. The highest grain yields were observed at the high rate of cattle manure addition (3X or 60.6 t ha^{-1}rate) (Table 3.3). Compared to urea alone, the addition of cattle manure alone or in combination with urea produced similar yield at high rates of manure.

Table 3.3. Grain yield in 2007 (oats), 2008 (canola) and 2009 (oats) at Dixon, Saskatchewan.

	Application rate (t ha^{-1})	2007 (kg ha^{-1})		2008 (kg ha^{-1})		2009 (kg ha^{-1})	
Control	**0**	3486†	(1353)‡	543	(342)	1753	(657)
Control-Disturbed	**0**	3644	(1116)	452	(324)	1846	(551)
Broadcast alone	**20.2**	4415	(375)	851	(435)	2614	(362)
	40.4	4570	(347)	857	(277)	2762	(334)
	60.6	5356	(1573)	902	(408)	3594	(535)
Broadcast and incorporated	**20.2**	4337	(929)	995	(426)	2742	(594)
	40.4	4600	(366)	858	(292)	3036	(710)
	60.6	4650	(512)	1171	(313)	3643	(349)
Subsurface banded	**20.2**	4557	(549)	660	(160)	3111	(590)
	40.4	4638	(257)	730	(317)	3848	(542)
	60.6	4702	(709)	1253	(382)	3505	(389)
Subsurface banded + urea	**20.2 + urea**	5103	(343)	2014	(362)	3623	(525)
	40.4 + urea	4853	(854)	2185	(472)	3908	(342)
	60.6 + urea	4909	(570)	1964	(223)	3550	(344)
Urea	**78 kg N ha^{-1}**	5098	(281)	1401	(401)	3784	(475)
$LSD_{(0.10)}$§		618		260		384	

† Means in the first column
‡ Standard deviation (±) of the means in the second column
§ Least significant difference at $P \leq 0.10$

Adding 78 kg N ha^{-1} of urea along with the solid cattle manure gave the highest yield at the 1X rate (20.2 t ha^{-1}). Therefore, supplementation with urea to account for the low N availability of SCM in the year of application would seem to be a good option if one desires to use a low rate of SCM to avoid P loading. Chang and Janzen (1996) reported that even after 20 years of annual SCM applications, only 56 % of the total N applied with the manure had been mineralized, which suggests that many applications of SCM over a very long time period would be necessary to produce a significant effect on crop yield due to relatively low availability of the cattle manure N in the initial years of application. There were no significant ($P \leq 0.10$) differences in oat crop grain yield between the three rate treatments of 20.2, 40.4 and 60.6 t ha^{-1} of broadcast alone, broadcast and incorporated and subsurface banded SCM treatments added to the treatment plots (Table 3.3). Straw biomass in the 2007 oats crop was significantly ($P \leq 0.10$) greater in the subsurface banded plus urea treatments compared to the control treatments (Appendix B. Table B.1). Oats through its extensive and root development can access soil nutrients at greater depths (Malhi et al., 2002; Malhi et al., 2006), explaining the general overall lack of large response to manure and fertilizer application.

3.5.2 2007 Crop year: Placement effects on yield

Comparing broadcast without incorporation application to a broadcast and incorporation application, the only significant difference in yield was observed at the high rate of SCM, with the broadcast without incorporation treatment surprisingly having a higher yield. This may be related to hot and dry conditions encountered during the summer of 2007 in which the amount of manure persisting on the surface as a result of no incorporation may have reduced surface temperatures and helped reduce evaporation. Lack of a general benefit of incorporation is also explained by the low ammonium content of the manure (Table 3.2) and therefore low potential for volatilization losses of the N contained in the manure. For the same rate of application, the band subsurface banded SCM was not significantly different in yield from the broadcast and incorporate, or broadcast applications.

3.5.3 2007 Oat crop nutrient concentrations and uptake

Grain N concentrations increased with increasing rate of SCM for the broadcast and incorporated, and subsurface banded treatment, but not for the broadcast without incorporation treatment (Table 3.4) Higher concentrations of nutrient in plant material are reflective of greater nutrient availability in the soil (Havlin et al., 2014). Lower plant N concentrations for the broadcast without incorporation than the other treatments indicates lower N recovery for SCM when broadcast than when incorporated or subsurface banded. The subsurface banded SCM has grain N and straw N concentrations (Appendix B. Table B.3), that are similar or slightly above the broadcast and incorporate treatments, and significantly higher than the broadcast without incorporation. A similar trend was noted for P concentration in grain and straw (Appendix B, Table B.2), with highest P concentration in the grain from the subsurface banded treatment (Table 3.5). Overall, there were not large differences in grain and straw nutrient concentrations between broadcast and incorporated and the subsurface banded treatments. The highest grain and straw N (Appendix B, Table B.3) concentrations were found in treatments where urea was added along with the SCM.

Table 3.4. Grain nitrogen concentrations (μg N g^{-1} of dry matter) in 2007 (oats), 2008 (canola) and 2009 (oats) at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(μg g^{-1})			
Control	**0**	13151[†]	(853)[‡]	24671	(2857)	14054	(646)
Control-disturbed	**0**	12785	(638)	24988	(7433)	14266	(1023)
Broadcast alone	**20.2**	12760	(805)	22419	(2393)	15182	(1122)
	40.4	11890	(224)	25338	(2269)	16053	(448)
	60.6	12635	(597)	28010	(6002)	15319	(1813)
Broadcast and incorporated	**20.2**	13332	(945)	26761	(641)	14362	(792)
	40.4	13473	(835)	25725	(3543)	16498	(1246)
	60.6	14448	(1344)	25664	(5938)	15738	(1018)
Subsurface banded	**20.2**	12780	(1156)	24195	(1824)	16378	(794)
	40.4	12065	(1512)	24485	(743)	16200	(912)
	60.6	14516	(1249)	27264	(788)	17410	(1657)
Subsurface banded + urea	**20.2 + urea**	16361	(1325)	32823	(4750)	17410	(1657)
	40.4 + urea	16933	(1190)	34117	(1619)	17420	(898)
	60.6 + urea	16518	(908)	38207	(4090)	16108	(475)
Urea	**78 kg N ha^{-1}**	15819	(1001)	26678	(1835)	14627	(700)
$LSD_{(0.10)}$[§]		1216		4419		1166	

[†] Means in the first column

[‡] Standard deviation (±) of the means in the second column

[§] Least significant difference at $P \leq 0.10$

Table 3.5. Grain phosphorus concentrations (µg P g^{-1} of dry matter) in 2007 (oats), 2008 (canola) and 2009 (oats) at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(µg g^{-1})			
Control	**0**	3900†	(244)‡	6367	(164)	3832	(731)
Control-disturbed	**0**	3825	(150)	6638	(265)	3337	(225)
	20.2	3750	(300)	6584	(243)	3598	(154)
Broadcast alone	**40.4**	3654	(108)	7117	(234)	3576	(51)
	60.6	3825	(377)	7168	(560)	3616	(270)
	20.2	3825	(287)	6927	(149)	3429	(129)
Broadcast and incorporated	**40.4**	3884	(410)	6985	(142)	3649	(145)
	60.6	4050	(300)	7121	(224)	3612	(136)
	20.2	3825	(450)	6635	(286)	3433	(158)
Subsurface banded	**40.4**	3825	(287)	7004	(241)	3562	(228)
	60.6	4125	(377)	7061	(122)	3604	(140)
	20.2 + urea	3825	(150)	6642	(574)	3742	(148)
Subsurface banded + urea	**40.4 + urea**	4050	(173)	7192	(177)	3660	(149)
	60.6 + urea	3975	(287)	7527	(450)	3697	(153)
Urea	**78 kg N ha^{-1}**	3375	(150)	5715	(352)	3425	(130)
$LSD_{(0.10)}$§		317		363		276	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

3.5.4 Soil properties in fall of 2007

Cattle manure addition caused some small but non-significant increases in EC (salinity) at the 0-15 cm depth (Table 3.6). There was no significant effect of application method on the EC. The soil pH (0-15 cm depth) was not significantly affected by treatment (Table 3.6). The OC concentration in the 0-15 cm depth increased with application of manure, for all methods of application and urea fertilizer application. However, there was no significant effect of manure placement on soil OC (Table 3.6).

Table 3.6. Soil pH, electrical conductivity and organic carbon (0-15 cm depth) at Dixon, Saskatchewan.

	Application rate (t ha^{-1})	pH 2007	pH 2008	pH 2009	Electrical conductivity (mS cm $^{-1}$) 2007	2008	2009	Organic carbon (%) 2007	2008	2009
Control	**0**	7.1	7.2	7.1	0.15	0.21	0.16	2.3	2.2	2.4
Control-disturbed	**0**	7.2	7.3	7.2	0.15	0.16	0.15	2.3	2.4	2.3
	20	6.9	7.1	7.0	0.18	0.21	0.19	2.6	2.5	2.4
Broadcast alone	**40**	7.6	7.7	7.2	0.26	0.28	0.26	2.6	2.6	2.7
	60	6.9	7.2	7.6	0.23	0.35	0.31	2.7	2.6	2.8
	20	7.2	7.6	7.2	0.20	0.15	0.17	2.6	2.7	2.7
Broadcast and incorporated	**40**	7.0	7.5	7.6	0.20	0.19	0.23	2.8	2.7	2.5
	60	7.1	7.9	7.2	0.23	0.28	0.28	2.6	2.1	2.9
	20	7.1	7.9	7.6	0.18	0.19	0.18	2.5	2.3	2.1
Subsurface banded	**40**	7.3	7.7	7.6	0.23	0.24	0.22	2.4	2.4	2.4
	60	6.7	7.2	7.2	0.34	0.18	0.31	2.8	2.7	2.5
	20 + urea	6.8	7.7	7.3	0.16	0.20	0.26	2.4	2.5	2.6
Subsurface banded + urea	**40 + urea**	7.0	7.4	7.1	0.20	0.16	0.25	2.6	2.6	2.6
	60 + urea	7.4	7.7	7.4	0.36	0.28	0.31	2.6	2.5	2.6
Urea	**78 kg N ha^{-1}**	6.5	7.7	7.4	0.28	0.19	0.20	2.6	2.3	2.5

The Modified Kelowna (MK) extractable P (0-15cm) was significantly increased by the single cattle manure application (Table 3.7). The MK extractable P increased from about 14 kg P ha^{-1} to greater than 60 kg P ha^{-1} at the highest rates of application. Below 15 cm, no significant increases in extractable P were observed (Appendix B. Table B.4). The large increase in soil test P from a single application is consistent with the high P content of this manure which had a greater impact on available P than that observed on a similar soil from a single application of LHM with a lower P content (Qian and Schoenau, 2000). For the same rate of application, the broadcast alone and broadcast with incorporation treatments resulted in very similar MK extractable P values in the 0-15 cm depth. Of note is that the high rate (3X or 60.6 t ha^{-1}) of subsurface banded SCM produced a significantly higher MK extractable P than the high rate of broadcast without, and with, incorporation. This suggests that there may be better soil adsorption of P with subsurface banded SCM when applying at high rates.

Table 3.7. Soil extractable phosphorus (0-15 cm depth) at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	14.2†	(5.0)‡	23.4	(20.0)	18.3	(11.8)
Control-disturbed	**0**	14.7	(3.2)	23.5	(9.6)	19.8	(6.6)
	20.2	25.9	(10.2)	42.3	(21.4)	62.3	(26.7)
Broadcast alone	**40.4**	41.7	(12.8)	77.0	(23.2)	132.4	(66.4)
	60.6	64.2	(17.6)	150.1	(51.1)	222.2	(36.8)
	20.2	33.6	(5.1)	68.4	(21.1)	70.0	(27.4)
Broadcast and incorporated	**40.4**	50.6	(8.5)	93.4	(37.0)	114.6	(58.3)
	60.6	60.3	(18.0)	93.3	(73.7)	177.1	(20.6)
	20.2	17.3	(5.4)	26.3	(10.1)	42.3	(16.7)
Subsurface banded	**40.4**	48.6	(42.4)	118.2	(109.6)	225.5	(122.4)
	60.6	114.7	(79.1)	145.9	(73.6)	204.9	(127.3)
	20.2 + urea	21.7	(7.3)	50.1	(30.6)	118.1	(91.6)
Subsurface banded + urea	**40.4 + urea**	26.2	(15.3)	46.7	(11.4)	104.5	(98.1)
	60.6 + urea	85.3	(60.4)	75.0	(27.6)	177.5	(78.5)
Urea	**78 kg N ha^{-1}**	13.1	(2.6)	38.3	(52.4)	30.4	(19.1)
LSD$_{(0.10)}$§		34.4		56.2		81.4	

† Means in the first column

‡ Standard deviation (±) in the second column

§ Least significant difference at $P \leq 0.10$

The residual soil nitrate in the fall of 2007 was generally low, with not much difference between the manured treatments, except for the 60.6 t ha^{-1} rate subsurface banded and subsurface banded plus urea treatments (Table 3.8). There was significant ($P \leq 0.10$) differences between the control treatment and high (60 t ha^{-1}) rate SCM treatments, reflecting low release of available N from 20.2 t ha^{-1} rate SCM treatments in the year of application. There was no significant rate effect and little difference in residual soil NO_3-N (Table 3.8) and NH_4-N (Table 3.9) content among placement methods. There was no significant rate effect and little difference in residual soil NO_3-N (Table 3.8) and NH_4-N (Table 3.9) content among placement methods in the 15-30 cm depth (Appendix B. Table B.5 and Table B.6). Overall, the highest residual nitrate contents were observed in the high rate of subsurface banded cattle manure plus urea treatment.

Table 3.8. Soil extractable nitrate-nitrogen (0-15 cm depth) at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	8.0†	(2.1)‡	5.7	(2.3)	6.6	(2.0)
Control-disturbed	**0**	7.7	(1.1)	5.5	(1.7)	4.6	(0.4)
	20.2	8.5	(2.6)	6.9	(4.3)	7.6	(2.5)
Broadcast alone	**40.4**	9.0	(1.5)	7.3	(1.2)	9.5	(3.0)
	60.6	8.6	(1.7)	11.1	(1.9)	10.3	(1.6)
	20.2	8.1	(1.3)	10.7	(2.7)	6.5	(1.3)
Broadcast and incorporated	**40.4**	10.0	(1.6)	9.9	(2.4)	7.3	(0.9)
	60.6	10.2	(1.7)	9.1	(5.2)	9.0	(1.7)
	20.2	7.3	(0.8)	6.3	(1.3)	5.9	(0.7)
Subsurface banded	**40.4**	7.3	(0.4)	7.9	(3.3)	7.8	(1.9)
	60.6	11.2	(3.5)	9.7	(4.3)	11.4	(3.5)
	20.2 + urea	8.2	(1.7)	10.5	(1.7)	8.5	(1.5)
Subsurface banded + urea	**40.4 + urea**	11.5	(3.4)	11.4	(3.0)	12.7	(3.2)
	60.6 + urea	17.0	(4.6)	15.5	(1.4)	15.0	(7.3)
Urea	**78 kg N ha^{-1}**	9.8	(5.5)	11.2	(3.7)	7.5	(1.4)
$LSD_{(0.10)}$§		3.1		3.0		3.2	

† Means in the first column

‡ Standard deviation (±) in the second column

§ Least significant difference at $P \leq 0.10$

Table 3.9. Soil extractable ammonium-nitrogen (0-15 cm depth) at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	6.3†	(2.8)‡	12.7	(2.7)	7.6	(2.3)
Control-disturbed	**0**	6.8	(3.5)	13.1	(3.8)	8.3	(1.2)
	20.2	5.4	(2.3)	10.9	(2.5)	7.7	(3.4)
Broadcast alone	**40.4**	5.6	(3.6)	15.0	(6.2)	7.7	(1.6)
	60.6	5.6	(1.6)	10.6	(3.3)	7.1	(1.7)
	20.2	6.8	(1.9)	11.8	(2.7)	7.5	(2.0)
Broadcast and incorporated	**40.4**	6.6	(2.6)	10.9	(3.7)	6.6	(1.1)
	60.6	5.5	(2.1)	10.9	(3.2)	8.2	(1.9)
	20.2	4.7	(2.9)	11.9	(3.0)	6.3	(0.8)
Subsurface banded	**40.4**	5.8	(3.1)	8.2	(3.9)	7.7	(1.6)
	60.6	5.0	(1.4)	12.7	(1.5)	9.5	(4.2)
	20.2 + urea	5.9	(1.9)	11.5	(4.3)	7.5	(1.7)
Subsurface banded + urea	**40.4 + urea**	7.5	(2.8)	13.2	(1.9)	7.4	(2.2)
	60.6 + urea	7.2	(3.8)	10.6	(4.2)	7.0	(1.1)
Urea	**78 kg N ha^{-1}**	7.1	(2.3)	15.7	(1.6)	8.5	(1.0)
LSD$_{(0.10)}$§		2.2		3.0		2.2	

† Means in the first column

‡ Standard deviation (±) in the second column

§ Least significant difference at $P \leq 0.10$

3.5.5 2008 Crop year: Rate effects on yield

In 2008, canola was grown at the site. Compared to the non-manured, unfertilized control treatments, manure and urea addition increased canola grain yield (Table 3.3). The 60.6 t ha^{-1} subsurface banded rate that produced significantly ($P \leq 0.10$) higher yield than the 20.2 and 40.4 t ha^{-1} in the broadcast and incorporated subsurface banded treatments. The greatest treatment effect was observed for the combination of urea plus subsurface banded solid cattle manure. The greater response of canola yield to treatments observed in 2008 as compared to oat yield in 2007 could be explained by the greater N nutrient requirement of canola compared to oats (Malhi et al., 2008). The treatments of 78 kg N ha^{-1} as urea plus subsurface banded cattle manure resulted in significantly higher canola yields than the other treatments, including urea alone. The benefit of the combined SCM and urea is attributed to urea providing additional plant available N, along with other nutrients that the SCM supplies such as P and sulfur. Canola straw biomass was significantly ($P \leq 0.10$) greater in the subsurface banded plus urea fertilizer treatments compared to the broadcast alone, broadcast and incorporated SCM treatments and the control treatment (Appendix B. Table B.1).

Mooleki et al. (2004) reported that a spring application of SCM at different rates using broadcast and incorporation application, on a Black Chernozemic soil at Humboldt, Saskatchewan, resulted in no significant yield increase for the canola crop. The authors reported that the SCM in their study contained limited available NH_4-N and a high C:N ratio that restricted mineralization potential in the year of application. Subsequent years of SCM application did result in an increase in canola grain yield which the authors attributed to release of available N over time (Mooleki et al., 2004). In the second year of the current study with only one previous application of SCM, there would have been little residual available N for the canola crop to utilize. When SCM was subsurface banded with urea, the available N in the fertilizer allowed for a greater canola crop yield response, compared to the broadcast alone, broadcast and incorporated and subsurface banded SCM treatments in 2008 (Table 3.3). The placement of SCM in a concentrated band with urea may potentially enhance microbial activity to release more nutrient contained in the manure to increase the canola crop yield. When compared to the crop yield obtained with the urea fertilizer alone, the addition of SCM, despite there being no rate effect, did increase grain yield (Table 3.3).

3.5.6 2008 Crop year: Placement effect on yield

There was an impact in 2008 of the SCM placement on canola yield with in-soil placement (broadcast and incorporate, subsurface banded) having higher yield than broadcast at the 60.6 t ha^{-1} application rate (Table 3.3). However at lower rates there was no significant influence of placement method. The subsurface banded treatment when combined with readily available N from the urea fertilizer significantly ($P \leq 0.10$) increased canola grain yield. As in 2007, the lack of a benefit of SCM incorporation or subsurface banding is likely related to the low NH_4 content of the SCM and low potential for volatilization losses of the N contained in the manure. The high 60.6 t ha^{-1} SCM rate in the broadcast and incorporated, subsurface banded produced higher grain yields while all three SCM application rates in the subsurface banded plus urea application method treatments produced the highest overall grain yields (Table 3.3).

3.5.7 2008 Canola crop nutrient concentrations and uptake

Canola grain N content was only slightly increased by cattle manure application, reflecting the relatively low availability of N contained in the SCM (Table 3.4). Both grain P and straw P (Appendix B. Table B.2) were significantly increased, reflecting the significant contribution of SCM P to plant available P in the soil (Table 3.7) (Qian and Schoenau, 2000). At the 20.2 t ha^{-1} SCM rate, grain and straw N (Appendix B. Table B.2) concentration tended to be higher for broadcast and incorporated and subsurface banded SCM treatments than broadcast only treatment, indicating greater recovery of N from in-soil placement, as has been observed in previous trials with liquid swine manure (Mooleki et al., 2002). This trend was also observed in 2007. This effect however, was not observed at higher rates. The 40.4 and 60.6 t ha^{-1} SCM rate for broadcast alone, broadcast and incorporated, subsurface banded and subsurface banded plus urea treatment had the highest plant P concentrations while the subsurface banded SCM plus urea treatment produced the highest plant N concentrations (Table 3.4).

3.5.8 Soil properties in fall of 2008

As in 2007, soil pH and salinity in 2008 were not significantly affected by SCM rate or placement (Table 3.6). As well, similar to the previous year, the OC concentration in the 0-15 cm was affected by SCM application, application rate and method of placement (Table 3.6). Manure application resulted in significant increases in MK extractable P again in the fall of 2008 (Table 3.7). After two successive manure applications, the general trend for soil test P values was to increase compared to fall of 2007, with values of ~150 kg extractable P ha^{-1} present in the 3X treatments. There were no discernible effects of placement. Of the 60.6 t ha^{-1} treatments, the broadcast and the subsurface banded treatments had higher soil test P than the broadcast and incorporated in the 0-15 cm depth (Table 3.7). Adding urea to the subsurface banded manure reduced the soil test P levels in the fall, presumably due to greater yield and manure P utilization by the crop. Extractable potassium levels were also nearly doubled.

The soil NO_3-N levels in the fall of 2008 tended to increase slightly with application rate, and, as in 2007, they were generally low. Also, again placement had no significant effect on soil NO_3-N (Table 3.8) and tended to depress NH_4-N (Table 3.9) in the 0-15 cm depth. Soil NO_3-N level in the subsurface banded plus urea 60.6 t ha^{-1} SCM treatment was significantly ($P \leq 0.10$)

greater than the control, broadcast alone and broadcast and incorporated treatments in the 15-30 cm depth (Appendix B. Table B.4).

3.5.9 2009 Crop year: Rate effects on yield

As in 2007 and 2008, SCM application treatments were made on the plots in spring of 2009 and oats were grown. A significant (*$P \leq 0.10$*) oat grain yield response to manure addition treatments compared to the non-manured, unfertilized control treatments was observed again in 2009 (Table 3.3), as for the crops in previous years. Unlike in 2007 and 2008, there was a rate effect in oat yield response in 2009, with the 3X (60.6 t ha^{-1}) manure treatments producing significantly (*$P \leq 0.10$*) higher oat yield than the 20 t ha^{-1} low rate (Table 3.3). There was a response to the supplemental addition of urea at the 20.2 t ha^{-1} (1X) rate of manure, but not at the 40.4 t ha^{-1} (2X) or 60.6 t ha^{-1} (3X) rates.

Since 2009 represents the third consecutive year on which manure was applied at these rates, it appears that greater mineralization of accumulated organic N in the soil is now taking place at the 40.4 and 60.6 t ha^{-1} manure rates to meet the crop nutrient requirements, especially at the 60.6 t ha^{-1} rate of addition. The 20 t ha^{-1} manure treatments continue to yield less than the urea treatments, suggesting that the supply of N from the annual application of 20.6 t ha^{-1} for 3 years is not yet sufficient to meet crop N requirements.

3.5.10 2009 Crop year: Placement effects on yield

For the effects of placement on oat grain yield in the last year of the study, 2009, the surface broadcast and the broadcast and incorporation treatments at the same rate of cattle manure had similar yield (Table 3.3). However, there was a trend for the subsurface banded manure to yield slightly higher than the broadcast alone, and broadcast and incorporate treatments, especially at the 40 t ha^{-1} SCM rate (2X) of manure addition. In previous years (2007 and 2008), there was no apparent benefit to subsurface banding (Table 3.3). A possible reason for a benefit that appears in year three of the experiment is that the subsurface banding has hastened the decomposition and release of available nutrients through mineralization. Placement of crop residues in contact with soil is well known to enhance decomposition rates (Campbell et al., 2007) and the lower degree of surface stratification of nutrient in the subsurface banded treatment, as the manure is concentrated in a band 10-13 cm below the surface, may also be favorable in reducing volatile losses of gaseous N to the atmosphere as ammonia during manure decomposition.

3.5.11 2009 Oat crop nutrient concentrations and uptake

Grain and straw N concentrations were increased by application of cattle manure, as observed in the previous two years (Table 3.4). The grain N concentrations in the banded treatment tended to be higher or similar to the broadcast and the broadcast and incorporate treatments, following trends observed in 2007 and 2008. The higher plant N concentrations along with the higher yields noted for subsurface banding, especially at the 1X (20.2 t ha^{-1}) rate, indicate that injection is providing some benefit in enhancing crop uptake and recovery of manure N, possibly by reducing ammonia volatilization losses or enhancing decomposition to available forms. The plant P concentrations were less affected by manure application than in 2008, likely a result of the greater ability of oats to scavenge soil P compared to canola (Table 3.5).

3.5.12 Soil properties in fall of 2009

Some small increases in EC were noted with manure application, reflecting the salts added in the manure, but there was no evidence of any salinity build-up (Table 3.6) that would cause injury to any crop, as EC values > 1 mS cm^{-1} are generally required to be of concern in manured soils (Japp, 2007). As well, similar to the previous two years in this study, the OC concentration in the 0-15 cm depth increased with application rate for broadcast alone and broadcast and incorporated SCM methods of application (Table 3.6). There was no significant effect of placement on pH, EC or OC concentration in the 0-15 cm depth (Table 3.6).

The soil test MK P increased from 18.3 kg P ha^{-1} at the 0-15 cm depth in the unfertilized control to > 200 kg P ha^{-1} in the 3X (60.6 t SCM ha^{-1}) treatment (Table 3.7). This is explained by the large amount of manure P, calculated to be ~ 500 kg P ha^{-1}, that was added to the soil in this treatment over the three years. These results again demonstrate that build-up of soil P can occur with cattle manure addition even over relatively short time periods when annual application rates are high. Manure placement method appeared to have relatively little influence on extractable P in the 0-15 cm depth (Table 3.7). The significantly greater extractable P level in the 15-30 cm depth at high application rates, could be due to a small amount of P moving below the 0-15 cm depth into the 15-30 cm depth by leaching (Appendix B. table B.4).

The soil NO_3-N levels in the 0-15 cm depth increased with manure application, and generally increased with increasing rate (Table 3.8), however, the amount of nitrate in the soil, even at the 60.6 t ha^{-1} yr^{-1} rate, was still low (< 15 kg NO_3-N ha^{-1}). Also there was no evidence of significant movement of nitrate below the 15 cm depth into the 15-30 cm (Appendix B. Table B.5), except for a slight elevation at the high rates of the subsurface banded manure plus urea treatment. The largest impact of manure addition observed in this study was on soil extractable P levels. These were greatly increased by addition of manure (Table 3.7).

3.5.13 Soil phosphorus and nitrogen supply rates in the 2009 season

Soil PO_4-P and NO_3-N supply rates were measured during the growing season from the beginning of June to the end of July, 2009 in the surface layer of soil using PRS probes. Soil P nutrient supply was assessed in the control treatment and the 60.6 t ha^{-1} (high rate) SCM broadcast alone, broadcast and incorporated, and subsurface banded SCM treatment plots and the urea fertilizer alone treatment (Fig. 3.5). Soil PO_4-P supply rates were significantly ($P \leq 0.10$) higher in manure amended soils than in the control treatment for all measurement periods (Fig. 3.5). Urea alone treatment also had slightly higher supply rates of PO_4-P than the control, which was significant at two measurement times. This may reflect some stimulated biological activity induced by the urea. Sustained soil PO_4-P supply rates in the top 1cm of soil throughout the sampling period to the end of July suggests continued P mobilization from the manure but may also reflect limited plant removal of P from the top 1 cm of soil by roots. The soil P supply rate was significantly affected by SCM placement method (Figure 3.5). Significantly higher soil P supply rates were observed for surface broadcast placement than for broadcast and incorporation and subsurface banding.

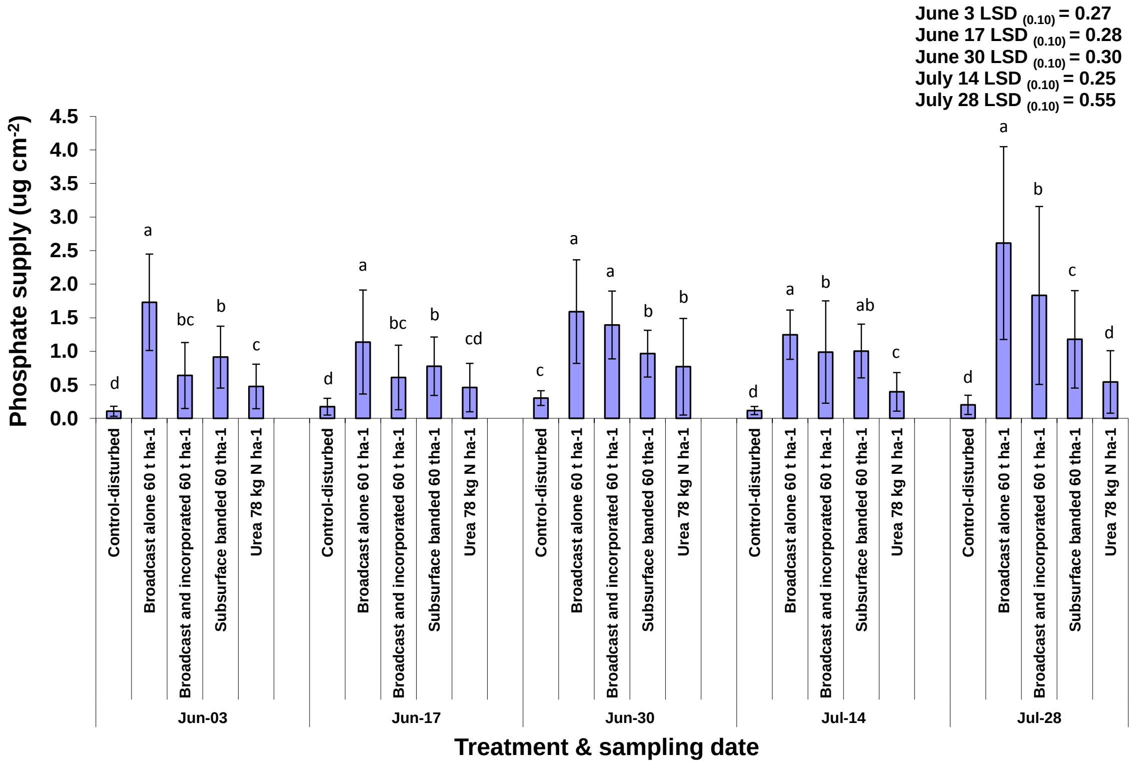

Fig. 3.5. Soil phosphate-phosphorus supply rates measured in the surface soil by Plant Root Simulator™ anion exchange membrane probes in 2009 at Dixon, Saskatchewan. Means followed by the same letter are not significantly different for that sampling date. Error bars denote standard deviation of the mean.

Subsurface banding treatment had the lowest soil PO_4-P supply rates in the surface soil at the middle and end measurement times. This could be due to the SCM P that was bound in the subsurface band, making it less available for plant P supply. The soil supply of PO_4-P in the broadcast alone SCM treatment is attributed to the SCM in this treatment being applied on the soil surface without incorporation. By the last sampling date of July 28th, soil supply of PO_4-P in the broadcast and incorporated and subsurface banded treatments had increased compared to the amounts measured in the four earlier sampling dates (Fig. 3.5). This could reflect the breakdown and decomposition of the SCM potentially due to an increase in soil temperature and the release of the P nutrient contained in the manure into exchangeable orthophosphate forms as noted with LHM in a previous study (Qian and Schoenau, 2000). The surface soil NO_3-N supply diminished as the crop year progressed into summer (Fig. 3.6).

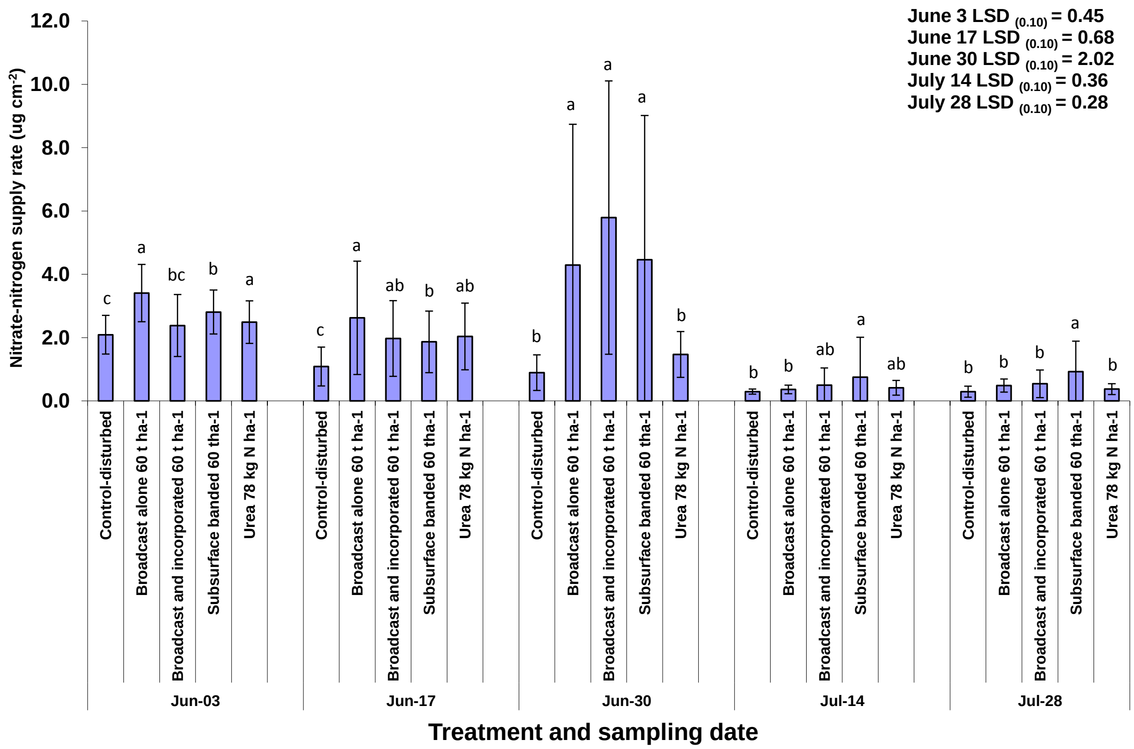

Fig. 3.6. Soil nitrate-nitrogen supply rates measured in the surface soil by Plant Root Simulator™ anion exchange membrane probes in 2009 at Dixon, Saskatchewan. Means followed by the same letter are not significantly different for that sampling date. Error bars denote standard deviation of the mean.

This reflects the consumption of nitrate by the crop, as nitrate is mobile and will move with water by mass flow to roots at depth. The spike in NO_3-N supply on June 30 may be explained by a large rain event prior to the June 30th sampling date that may have enhanced mineralization and nitrification of the SCM organic nitrogen (Fig. 3.6). For the most part, early on in the growing season the manure and urea treatments had significantly higher NO_3-N supply rates than the non-manured, unfertilized control. In-soil placement treatments tended to have lower nitrate supply early on in the season but by the end the subsurface banded had slightly but significantly higher nitrate supply rate in the surface soil (Fig. 3.6). The high C:N ratio of SCM would slow mineralization potential initially, however, greater moisture and microbial decomposition arising from placement in the soil may accelerate the immobilization – remineralization (Doran, 1980).

3.5.14 Release of phosphorus and nitrogen from canola residues

Above ground canola plant residue collected after harvest operations was not significantly ($P \leq 0.10$) different among treatments in total P concentration. This was the case for both unleached and leached (residue immersed in water and frozen for 24 hours) residues (Fig. 3.7). There was found to be a decrease in total P concentration as a result of the leaching-freezing treatment of the residue in all treatments based on comparison of the unleached to the leached plant residues (Fig. 3.7).

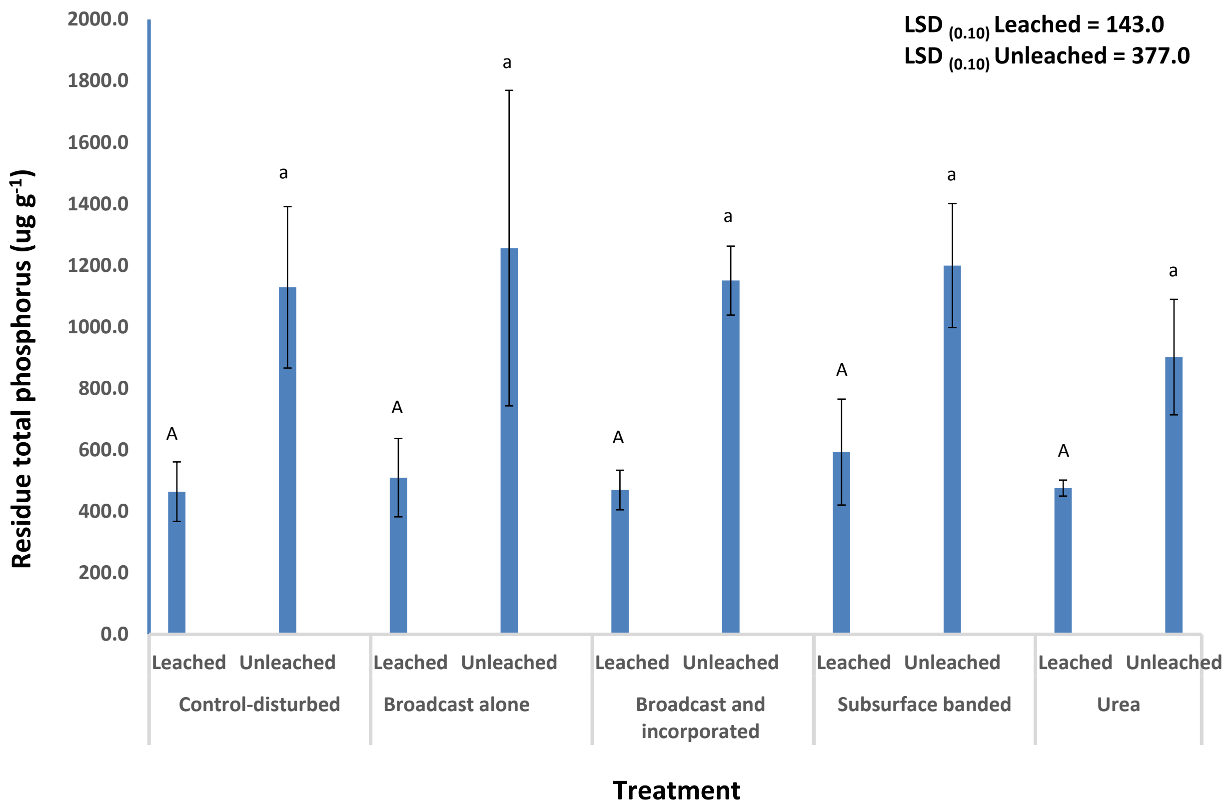

Fig. 3.7. Canola plant after-harvest residue total phosphorus concentrations in 2008 at a rate of 60 t ha^{-1} for the broadcast alone, broadcast and incorporated and subsurface banded solid cattle manure treatments and a rate of 78 kg N ha^{-1} for the urea applied treatment at Dixon, Saskatchewan. Means followed by the same letter are not significantly different at $P \leq 0.10$. Error bars denote standard deviation of the mean.

Unlike the straw and grain P concentrations in the harvested canola samples, the P concentrations in the residue collected from the manure treatments was not significantly higher than the non-manured control. This suggests that some P may already have been lost from the residue in the time period from harvest at the end of August to the time of residue collection in October. As such, there was a lack of a detectable manure placement effect on canola residue P content.

Similar to P, there were no significant ($P \leq 0.10$) differences in residue total N contents among treatments for both unleached and leached (immersed in water and frozen for 24 h) residues (Fig. 3.8). The leached and frozen residues had apparently lost the equivalent of about 1000 $\mu g\ g^{-1}$ total N in the three SCM treatments as a result of the leaching and freezing. Overall the magnitude of reduction in N content of the residues was less than observed for P. This is explained by a higher proportion of P in water soluble form in crop residue as compared to N, where more of the N is bound in organic forms that are not easily removed by water (Qian and Schoenau, 1995). In a corn, soybean and wheat residue leaching study conducted on a Nebraska field receiving animal manure, residues that were collected and subjected to addition of water in a lab over a period of time revealed that type of residue and residue/water contact time affected the leaching and sorption of P and N (Cermak et al., 2004; Schnepf and Cox, 2006).

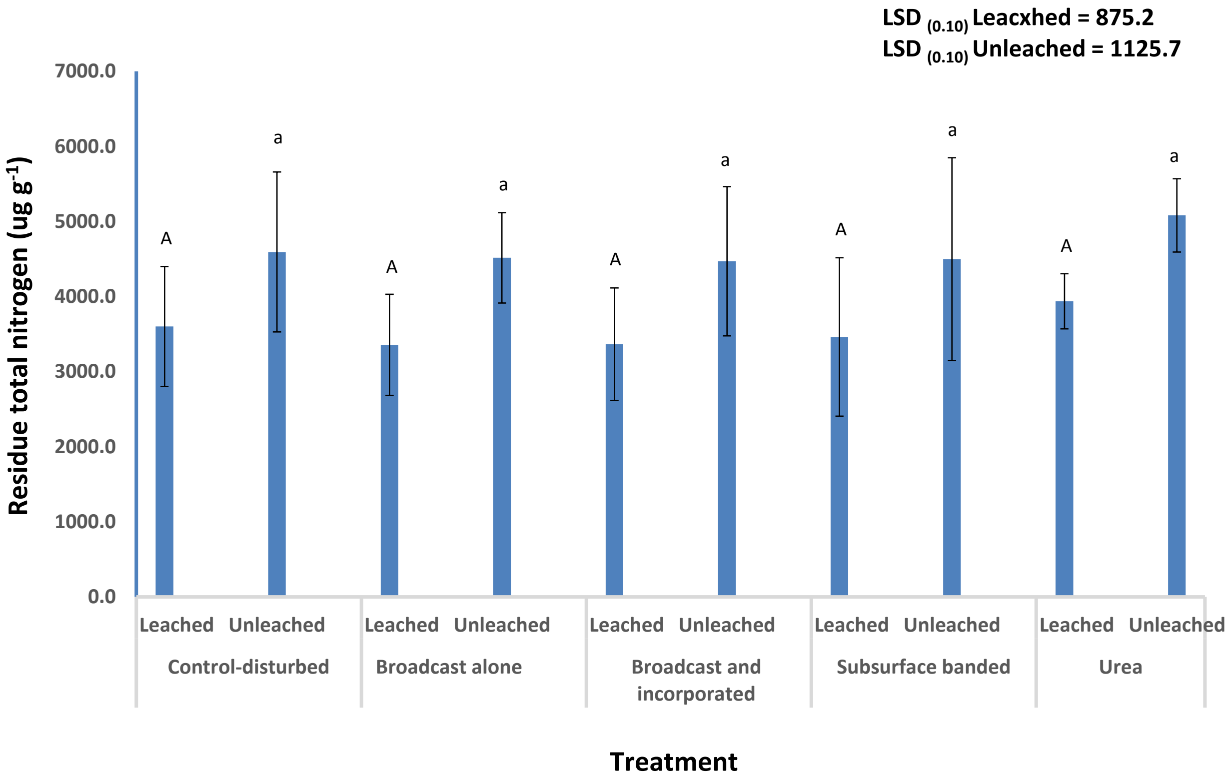

Fig. 3.8. Canola plant after-harvest residue total nitrogen in 2008 at a rate of 60 t ha^{-1} for the broadcast alone, broadcast and incorporated and subsurface banded solid cattle manure treatments and a rate of 78 kg N ha^{-1} for the urea applied treatment at Dixon, Saskatchewan. Means followed by the same letter are not significantly different at $P \leq 0.10$. Error bars denote standard deviation of the mean.

The authors reported that wheat residues sorbed PO_4-P at greater rates, as the time of immersion in water increased, while for corn and soybean residues the PO_4-P leaching increased as immersion time increased. Although there was no differences between SCM treatments in amount of P and N in canola plant residues that were subjected to leaching, the N and especially P content in leached residues was lower than unleached residues, indicating that the fresh residues released considerable amounts of these nutrients after being subjected to a one time leaching event.

3.6 Conclusion

Rate of manure application and application method had a limited effect on enhancing crop yields and nutrient uptake over the 2007, 2008 and 2009 growing seasons at the Dixon site. Manure application increased yields over the non-manured, unfertilized controls, but the effect of increasing rate and placement methods was usually not significant. In-soil placement through incorporation or subsurface banding resulted in higher canola yield than broadcast alone in 2008 and in the final year of the study in 2009, subsurface banding produced higher oat yield than other placement methods but only at the 40.4 t ha^{-1} rate. Addition of urea fertilizer along with manure resulted in the greatest yield benefits. The high content of organic N and very low plant available NH_4-N kept more of the N in a plant unavailable form. Overall, while SCM application can enhance crop yields at the rates that were evaluated, better responses may be anticipated for high nutrient requiring crops like canola when the manure is combined with commercial N fertilizer. A lack of crop removal of P and N could potentially increase the potential for lateral and/or vertical movement of these nutrients. Subsurface banding of SCM or incorporation of broadcast manure did not generally produce large significant agronomic benefits in yield and nutrient content compared to broadcasting alone. Although no economic analysis was conducted regarding subsurface banding, it likely to be more expensive to subsurface band SCM as opposed to broadcast alone and/or broadcast and incorporate.

Manure amendment and placement method had a more pronounced effect on soil P than N, consistent with its higher content of P, particularly soluble P. Soil P supply was greatly increased by SCM amendment and at the end of the three-year period surface soil P supply rates measured over the season were significantly higher in broadcast alone treatments compared to in soil placement via incorporation or subsurface banding. Observed loss of P from crop residues by water leaching could be a significant mechanism that may also influence the degree to which P is transported off site. However, the application of manure and its placement did not affect the amount of P or N removed from post-harvest canola crop residue in a simulated leaching. It would seem that perhaps the interaction of the run-off water with the mineral soil itself, as simulated in the PRS™ probe measurement, could be a more important potential influence of placement. The impact of manure application and placement on transport in water is covered in subsequent chapters in this thesis.

4. RELATIONSHIP BETWEEN MANURE MANAGEMENT APPLICATION PRACTICES AND PHOSPHORUS AND NITROGEN EXPORT IN SNOWMELT RUN-OFF WATER FROM A BLACK CHERNOZEM

4.1 Preface

Application of animal manures to agricultural fields was shown to be an effective practice for increasing soil fertility and crop yield as revealed in the study reported on in Chapter 3. However, the environmental effects of repeated manure applications on surface and groundwater quality can be detrimental if excessive amounts of manure-derived phosphorus (P) and nitrogen (N) are transported by overland flow or leached as a result of high moisture events such as spring snowmelt. Excess nutrients contained in the animal manure applied that are not taken up by the growing crop or adsorbed to soil constituents can become a non-point source pollutant for surface and/or subsurface water bodies. The research conducted in this chapter (Chapter 4) addresses specifically the relationship between manure management practices and the amount of phosphorus and nitrogen transported off the soil in simulated snowmelt run-off. Placement of solid cattle manure (SCM) in a concentrated subsurface band may reduce potential for surface runoff transport due to positioning of the manure nutrient further away from the surface flow. However, this effect may be offset by enhanced decomposition of the SCM and release of soluble reactive phosphorus (SRP), as well as providing a subsurface channel for lateral movement of nutrient below the surface. The research described in this chapter uses a novel method of simulating snowmelt water transport as affected by manure placement (broadcast, broadcast and incorporate, subsurface band), type such as SCM and liquid hog manure (LHM) and rate treatments imposed in small plot replicated trials in east-central Saskatchewan. An intact slab of soil is removed and exposed to simulated snowmelt run-off under controlled environment conditions, with two common spring melting regimes examined: thawing and frozen soil surface.

4.2 Abstract

In Saskatchewan, soil nutrients released from land-applied solid cattle manure (SCM) and liquid hog manure (LHM) could be subject to off-field export via spring surface run-off water and/or subsurface leaching from melting snow. The objective of this study was to determine how the placement of SCM and LHM using surface and subsurface application methods affects the amounts of soluble reactive phosphorus (SRP), nitrate-nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) exported in simulated snowmelt run-off. Intact soil slabs were collected post-harvest in Oct. 2008 and Oct. 2009 from an annually cropped Black Chernozem in east-central Saskatchewan having treatments of: 1) a control, with no SCM or urea fertilizer added and 2) SCM applied at a rate of 60.6 t ha^{-1} for 2 years as: surface broadcast, broadcast and incorporated and subsurface banded. For comparison purposes, intact soil slab monoliths were collected post-harvest in Oct. 2009 from an annually cropped Black Chernozem in east-central Saskatchewan having treatments of: 1) a control, with no LHM or urea fertilizer added; 2) LHM broadcast and incorporated at a rate of 37,000 L ha^{-1} for 12 years; and 3) LHM subsurface banded at rates of 37,000 L ha^{-1} and 148,000 L ha^{-1} for 12 years. Run-off water and leachate were collected under two different simulated prairie spring melt conditions: 1) thawing soil slabs containing snow that slowly melted on the surface; and 2) frozen soil slabs with run-off water applied to the surface and allowed to run-off across the frozen soil surface. Export of SRP in the thawing soil slabs that had SCM applied in subsurface bands was 0.51 kg P ha^{-1} and was significantly higher than the non-manured control (0.07 kg P ha^{-1}). Dissolved NO_3-N exported in water running across the frozen soil slabs was highest in the broadcast and incorporated treatment (0.30 kg N ha^{-1}). All SCM manured treatments had higher export of nitrate (0.2-0.25 kg NO_3-N ha^{-1}) compared to the non-manured control (0.07 kg ha^{-1}). There was no significant ($P \leq 0.10$) effect of placement method on SRP, NO_3-N and NH_4-N export on thawing or frozen SCM soil slabs. Export of SRP was less in LHM treatments than SCM treatments. In thawing soil slabs with 148,000 L ha^{-1} LHM treatment, the P export was 0.05 kg P ha^{-1} and was greater than the control treatment (0.01 kg ha^{-1}). Rate of application and manure type appears to be more important than method of placement in influencing P and N transport in melt water on these soils.

4.3 Introduction

Application of animal manure for its nutrient content and ability to aid in building soil organic matter is a common practice in western Canada in locations where animal manures are abundant. Nutrients such as phosphorus (P) and nitrogen (N) in manures can be effectively utilized for crop production. However, in soils receiving large application rates of animal manures, elevated transport of dissolved and particulate P and N off-field by water can be of concern in soils that become overloaded in these nutrients. For example, since the 1980s; the health of Lake Winnipeg has decreased due to excessive dissolved P and N loading from non-point sources including natural ecosystems, urban sources, atmospheric deposition as well as surrounding agricultural systems (Lake Winnipeg Stewardship Board, 2006). Beneficial management practices have been identified in an attempt to reduce the excess nutrients exported offsite to surface and subsurface water bodies (Schnepf and Cox, 2006). Much attention has been directed towards controlling point source contamination of surface and subsurface water bodies; however, non-point source contamination, such as off-field movement of nutrients from golf courses, urban lawns and agricultural fields, into surface and subsurface water bodies is difficult to identify and control (Sharpley et al., 2001).

Some agricultural fields have evolved from serving as sinks for nutrients such as P and N, to nutrient sources due to fertilizer application beyond crop nutrient demand (Sharpley et al., 2001). The desired P and N nutrient management in agriculture is to meet crop nutrient demand with little residual nutrient that is susceptible to loss mechanisms such as leaching, denitrification or export from the field in water. Practicing no-till soil conservation has been identified as one management method that reduces the amount of particulate nutrients carried by eroding sediment that is removed from agricultural fields, and this practice has been widely adopted by growers on the Canadian prairies. However, it was reported early on that dissolved nutrients can be more easily exported via surface and subsurface water in these minimal low disturbance (Baker and Laflen, 1983; Langdale et al., 1985; Sharpley and Smith, 1994; Zhao et al., 2001).

There has been a desire to more closely monitor and control the dissolved P movement off fields receiving annual or semi-annual applications of animal manure (Sharpley et al., 2005). Agricultural fields that are under a no-till management have been documented as having greater dissolved P losses in surface run-off, compared to conventional tilled fields due to the stratification of P with depth (Mueller et al., 1984; Sharpley and Smith, 1994), with a greater amount of P being concentrated in the upper surface portion of the soil (Butler and Coale, 2005; Guertal et al., 1991; Tiessen et al., 2010). Sharpley et al. (2005) observed strong correlation between P losses in run-off water and soil P availability at the 0.1-3.7 cm depth; namely as soil P increased in this zone, the greater the observed potential for soil release of P to run-off water which has also been reported elsewhere (Vadas et al., 2005).

Phosphorus and N export in run-off water can be affected by the rate, method and seasonal timing of manure application. Phosphorus and N in manures such as SCM or LHM that are directly applied to the soil surface without incorporation, may not interact with soil particles that would otherwise help to retain them through adsorption and formation of insoluble complexes (Vadas et al., 2004). Mooleki et al. (2002) reported greater crop yields and larger N recovery when LHM was subsurface banded compared to broadcast applications. Some studies have reported that the timing of animal manure application influences the forms and/or amounts of nutrients exported offsite. Klausner et al. (1976) suggested that fall pre-snowfall application of manure reduces N nutrient loss compared to winter manure application. When manure is applied during the spring prior to field operations (e.g., tillage, seeding and harrowing) the manure P is incorporated into the soil, which is commonly believed to reduce the amount of P exported via run-off.

A large portion of the nutrient loss research has been conducted in areas of Canada or the United States where run-off from rainfall events accounts for the majority of nutrient export. Previous research conducted in western Canada has reported that soil losses from spring snowmelt can be greater than erosion from rainfall (Chanasyk and Woytowich, 1987; McConkey et al., 1997; Van Vliet and Hall, 1991). In regions of the northern Great Plains such as Saskatchewan, spring snowmelt is the major moisture recharge event of the year. Snowfall can account for as much as 30 % of the annual precipitation received (Cutforth et al., 1999) and accumulates through several months, subsequently melting and running over thawing and frozen soil when spring temperatures begin to increase (Li et al., 2011). Snowmelt run-off can exceed rainfall run-off due to frozen soils with limited water infiltration (Granger et al., 1984; Hansen et al., 2000; Young and Mutchler, 1976). The prolonged period in which snowmelt occurs favors more saturated conditions within the soil surface, which enhances the release of dissolved nutrient forms (Bechmann et al., 2005; Little et al., 2007; Ontkean et al., 2005).

Snowmelt run-off has less erosive ability compared to run-off from rainfall. The kinetic energy generated by the force of raindrops contacting the soil surface can cause more aggregate breakdown, soil particle detachment and movement of particles with the run-off water (Li et al., 2011). Glozier et al. (2006) reported that approximately two-thirds of the N and P removal due to run-off from snowmelt in southern Manitoba occurred in a dissolved inorganic form. Little et al. (2007) reported that in Alberta, Canada, over 90 % of the P removed by spring snowmelt was in a dissolved inorganic form. Fleming and Fraser (2000) have reported that frozen or unthawed bare soils do not allow infiltration of nutrients such as P and N. Research has also been conducted into subsurface pathways for P loss (Sims et al., 1998). Jensen et al. (1998) and Stamm et al. (1998) have reported that most of the P leaching is likely through shallow macropore preferential flow. In soils that are thawing at the surface but remain frozen underneath in early spring, much of the flow below the soil surface may be lateral flow above the frozen layer.

Despite several studies that have examined water transport pathways in general, it is evident that limited information exists specifically on the nature and extent of SRP and N transport in snowmelt water in soils receiving animal manure applications in western Canada. Even less information exists regarding multi-year animal manure applications at different rates and the effect of different application methods. Subsurface injection or banding of manure can be beneficial to a crop, such as increased plant nutrient uptake, increased bioavailability of soil nutrients and enhanced crop growth (see Chapters 2 and 3). However the effects on nutrient export in snowmelt run-off have not been evaluated in western Canadian soils.

Therefore the objective of the research in this chapter was to determine the effect of surface and subsurface water flow arising from snowmelt on the nutrient export from soils with different manure management histories. A novel methodology was developed for collecting intact soil slab monoliths from replicated field plots. This was followed by the development of a technique for simulating melting snow conditions and run-off under two common spring scenarios: 1) where snowmelt water is allowed to infiltrate and move laterally below the soil surface in thawing soil and 2) a condition in which melt water moves rapidly across a frozen surface. It was hypothesized that P and N movement from soil amended with manure would be enhanced compared to unamended controls, that in-soil placement would reduce nutrient export in surface run-off, greater export of P would occur from SCM amended soil, and that export would be greater from snow melting on thawing soil that allows the snowmelt water to interact with the soil compared to melt water rapidly passing across frozen soil.

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4.4 Materials and Methods

4.4.1 Site description

The SCM and LHM studies were conducted near Dixon, Saskatchewan (Dixon site) on two adjacent areas of the same field (legal location NW 21-37-23-W2) within the Rural Municipality of Humboldt. The site description has been provided previously in section 3.4.2. The soil at the site belongs to the Cudworth Association and is a Black Chernozemic soil formed in calcareous, silty, lacustrine parent materials and having a loam surface texture (Saskatchewan Soil Survey 1989). The soil at this site occurs on a gently sloping land surface and has a few limitations that hinder agricultural activity. Identified limitations include insufficient moisture holding capacity and some salinity (covering 10-20% of the landscape), occurring mostly in sloughs and low lying areas (Saskatchewan Soil Survey, 1989). Soil pH in the 0-15 cm depth is 7.9, electrical conductivity is 0.1 dS m^{-1} and soil organic carbon is 2.5%. This field site is only slightly stony and has a low susceptibility to wind and water erosion (Saskatchewan Soil Survey, 1989).

4.4.2 Manure treatments

The SCM injection study at Dixon was established before spring seeding operations commenced in June 2007, with SCM applied using Prairie Agricultural Machinery Institute's (PAMI) SCM subsurface banding applicator machine as described in Chapter 3. The SCM field trial plots (3.05 x 6.09 m) were set up as a randomized complete block design, replicated four times. The SCM treatments were applied in June 2007, May 2008 and May 2009. A description of field seeding of crops and dates seeded was previously described in section 3.4.4. Treatments included an undisturbed control plot with no manure or fertilizer applied, and another control with no manure or fertilizer applied but with disturbance of the soil using the coulter openers of the SCM injector machine. The SCM was applied using three application procedures; 1) broadcast application where SCM was applied on the soil surface (no incorporation), 2) broadcast and incorporated where SCM was applied on the soil surface and then incorporated using a disk, 3) subsurface banding, where SCM was subsurface placed in bands using the PAMI SCM bander machine (in six subsurface trenches with 60 cm coulter openers spaced 30 cm apart, applying the SCM product in bands 10-13 cm in depth). Twenty cm closing wheels covered the exposed or banded trench with soil. The rate of SCM applied was equal to 300 kg total N ha^{-1}, at a rate of approximately 60.6 t ha^{-1}, and may be considered triple the rate of annually applied N (approximately 100 kg N ha^{-1}) that would be recommended as commercial fertilizer to meet typical crop requirements in the canola-oat rotation.

The SCM applied in the three-year field trial was obtained from the Poundmaker Feedlot, which is located approximately 8 km east of the town of Lanigan, SK. Phosphorus and N contents of the SCM applied in 2007, 2008 and 2009 are listed in Table 4.1. Due to variation in manure P content over the years, the P applied in the SCM treatments ranged from 150 kg P ha^{-1} in 2008 to 213 kg P ha^{-1} in 2009. Applied Total N in the SCM ranged from 180 kg N ha^{-1} in 2008 to 561 kg N ha^{-1} in 2009. Applied ammonium-nitrogen (NH_4-N) in the SCM was 0.15 kg NH_4-N ha^{-1} in 2007 and 2008, and 0.18 kg NH_4-N ha^{-1} in 2009.

The LHM trials that were sampled for comparison purposes were established in October of 1996. In this trial, each year after harvesting operations were completed, application of LHM was made using PAMI's LHM subsurface injector applicator truck as described by Mooleki et al. (2002). Soil slab monolith collection was conducted in Oct. 2009 prior to application of LHM. The LHM field trial plots (3.05 x 30.48 m) were set up as a randomized complete block design and replicated four times. Treatments were applied in October, post-harvest, every year for the duration of the 12-year long-term LHM study. The field was seeded to canola in late May of 2008, and to barley (*Hordeum vulgare*) in early June 2009. Treatments included a control plot with no manure or fertilizer being applied and disturbance of the soil using the coulter openers of the PAMI LHM subsurface injection applicator truck. Liquid hog manure was applied using two application procedures; 1) subsurface injection where LHM was subsurface banded and placed in a band using the PAMI LHM subsurface injection machine in six subsurface bands using 60 cm diameter coulter openers spaced 30 cm apart applying the LHM 10-13 cm deep, and 2) broadcast of LHM across the soil surface followed by incorporation after 24 hr.

Table 4.1. Rates of phosphorus, total N and ammonium N applied as manure from 2007-2009 in the solid cattle manure trials at Dixon, Saskatchewan.

Year of Application	Treatment†	Total P‡	Total N§	NH_4-N¶	Application method
	($t\ ha^{-1}$)	($kg\ ha^{-1}$)			
2007	0	0	0	0	with no incorporation, but disturbance#
	60.6	168	300	0.15	broadcast only
	60.6	168	300	0.15	broadcast and incorporated
	60.6	168	300	0.15	subsurface banded
2008	0	0	0	0	with no incorporation, but disturbance#
	60.6	150	180	0.15	broadcast only
	60.6	150	180	0.15	broadcast and incorporated
	60.6	150	180	0.15	subsurface banded
2009	0	0	0	0	with no incorporation, but disturbance#
	60.6	213	561	0.18	broadcast only
	60.6	213	561	0.18	broadcast and incorporated
	60.6	213	561	0.18	subsurface banded

† Application rate based on wet weight
‡ Total phosphorus from 3 years of solid cattle manure application
§ Total nitrogen from 3 years of solid cattle manure application
¶ Ammonium nitrogen from 3 years of solid cattle manure application
# No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

Manure sub-samples for both the SCM and LHM applications for each year of application were obtained from the application equipment at the time of treatment application in the field plots. From 1997-2007, the annual application rates of LHM were approximately 90 (37, 000 L ha^{-1}) and

350 (148,000 L ha^{-1}) kg total N ha^{-1} per year, and 6 kg total P ha^{-1} and 25 kg total P ha^{-1} per year on the low and high rate treatments respectively (Table 4.2).

Table 4.2. Treatments from 1997-2007, 2008 and 2009 in the twelve-year liquid hog manure study at Dixon, Saskatchewan.

Year of Application	Treatment†	P rate‡	Total N rate§	NH_4-N rate¶	Application method
	(L ha^{-1})		(kg ha^{-1})		
1997-2007	0	0	0	0	with no incorporation, but disturbance#
	37,000	62	875		hog manure subsurface injected
	148,000	248	3500		
	37,000	62	875		hog manure broadcast and incorporated
2008	0	0	0	0	with no incorporation, but disturbance#
	37,000	4	68	61	hog manure subsurface injected
	148,000	16	272	244	
	37,000	4	68	61	hog manure broadcast and incorporated
2009	0	0	0	0	with no incorporation, but disturbance
	37,000	7	79	69	hog manure subsurface injected
	148,000	28	316	276	
	37,000	7	79	69	hog manure broadcast and incorporated after 24 h

† Application rate based on wet weight
‡ Total phosphorus from 12 years of liquid hog manure application
§ Total nitrogen from 12 years of liquid hog manure application
¶ Ammonium nitrogen from 12 years of liquid hog manure application
# No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

The total N that was applied in the 12-year long-term LHM trial in the years that encompassed this study (2008 and 2009) slightly ranged from 68 kg N ha^{-1} in the 2008 low application rate treatment to 79 kg N ha^{-1} in 2009, while total P ranged from 4 kg P ha^{-1} to 7 kg P ha^{-1} in the same treatments

(Table 4.2). Phosphorus that was added over the 12 years in the LHM treatments at the 37,000 L ha^{-1} rate was 73 kg P ha^{-1} and added at the 148,000 L ha^{-1} rate was 292 kg P ha^{-1}.

4.4.3 Soil sampling and analysis

Soil samples from the SCM study and 12 year long-term LHM study were obtained from each of the treatment plots post-harvest in Oct. 2008 and Oct. 2009 using a truck mounted soil sampling coring device. Soil samples were analyzed for available nitrate-nitrogen (NO_3-N) and NH_4-N by extracting with 2 *M* potassium chloride and measuring the ion concentrations colorimetrically using a Technicon Autoanalyzer II (Keeney and Nelson, 1982). Soil extractable P was determined by a modified Kelowna method (Qian et al., 1994).

The extractable P measured in the 0-15 cm depth post-harvest at the 3 year SCM site increased to over 170 kg P ha^{-1} in the three manure treatments by fall 2009 compared to about 20 kg P ha^{-1} in the unmanured control plots (Table 4.3), reflecting the high amount of P added in the cattle manure. Only a small amount of inorganic N accumulated in the soil from the application of SCM, and soil extractable NO_3-N levels in the SCM site were 9-11 kg NO_3-N ha^{-1} in the three manure treatments in both the fall of 2008 and 2009 (Table 4.3). Soil extractable NH_4-N decreased slightly from 10 kg NH_4-N ha^{-1} in the three treatments in 2008 to less than 9 kg NH_4-N ha^{-1} in 2009 (Table 4.3). Low accumulations of ammonium and nitrate in the soil are anticipated with SCM due to low ammonium content and large amount of organic N that mineralizes only very slowly, as discussed in Chapter 3.

Soil extractable P measured in the 0-30 cm depth post-harvest at the 12 year LHM site, prior to LHM application in fall 2008 and 2009 was similar among treatments in 2008 and 2009. In 2008, MK-P ranged from 20.7 kg P ha^{-1} in the low rate broadcast and incorporated to 31.3 kg P ha^{-1} in the high rate subsurface banded versus 24.6 kg P ha^{-1} in the unmanured control (Table 4.4). Soil extractable P levels in the LHM treatments in the fall of 2009 were similar, and slightly lower than in the fall of 2008. Lack of large influence of long-term application of LHM on soil extractable P content is consistent with amounts of P added in LHM over the years (5 to 25 kg P ha^{-1} yr^{-1}) that are similar to P removed in crop harvest each year. Soil extractable NO_3-N levels in fall of 2008 in the 0-30 cm depth at the LHM site were 9 kg NO_3-N ha^{-1} in the control, 12 kg NO_3-N ha^{-1} in the low rate broadcast and incorporate, 51 kg NO_3-N ha^{-1} in the low rate subsurface banded and 266 kg NO_3-N ha^{-1} in the high rate subsurface banded treatment (Table 4.4). Soil extractable NH_4-

N in the 0-30 cm depth was 24-26 kg NH_4-N ha^{-1} in three LHM treatments and the control in 2008. In fall 2009 samples, soil extractable NO_3-N levels were again about four times higher in the high rate subsurface banded soils compared to the lower rate treated plots (Table 4.4). Accumulation of nitrate rather than phosphate in the LHM soil is expected with 12 years of annual addition of about 300 kg N ha^{-1}, which is an amount that greatly exceeds removal in crop harvest.

Table 4.3. Extractable soil nutrients (0-15 cm) in the solid cattle manure trials sampled post-harvest in 2008 and 2009 at Dixon, Saskatchewan.

Year of Application	Treatment†	MKP‡		NO_3-N		NH_4-N		Application method
	(t ha^{-1})	(kg ha^{-1})						
2008	0	23.5§	(9.6)¶	5.5	(1.7)	13.1	(3.8)	with no incorporation, but disturbance#
	60.6	150.1	(51.1)	11.1	(1.9)	10.6	(3.3)	broadcast only
	60.6	93.3	(73.7)	9.1	(5.2)	10.9	(3.2)	broadcast and incorporated
	60.6	145.9	(73.6)	9.7	(4.3)	12.7	(2.7)	subsurface banded
	LSD $_{(0.10)}$††	56.2		3.0		3.0		
2009	0	19.8	(6.6)	4.6	(0.4)	8.3	(1.2)	with no incorporation, but disturbance#
	60.6	222.2	(36.8)	10.3	(1.6)	7.1	(1.7)	cattle manure broadcast only
	60.6	177.1	(20.6)	9	(1.7)	8.2	(1.9)	cattle manure broadcast and incorporated
	60.6	204.9	(127.3)	11.4	(3.5)	9.5	(4.2)	cattle manure subsurface banded
	LSD $_{(0.10)}$	81.4		3.2		2.2		

† Application rate based on wet weight
‡ Modified Kelowna extractable P
§ Means in the first column
¶ Standard deviations (±) of the mean in the second column
# No application of manure and soil disturbance with PAMI manure applicator inserted in soil
†† Least significant difference ($P \leq 0.10$)

Table 4.4. Extractable soil nutrients (0-30 cm) in the liquid hog manure trials that were sampled post-harvest in 2008 and 2009 at Dixon, Saskatchewan.

Year of Application	Treatment†	MKP‡		NO_3-N		NH_4-N		Application method
	(L ha^{-1})	(kg ha^{-1})						
2008	0	24.6§	(15.0)¶	9.3	(1.8)	26.4	(5.4)	with no incorporation, but disturbance#
	37,000	26.4	(12.9)	50.7	(16.5)	25.0	(8.5)	hog manure subsurface injected
	148,000	31.3	(16.4)	266.4	(231.6)	26.4	(5.8)	
	37,000	20.7	(8.3)	11.7	(4.5)	24.3	(5.5)	hog manure broadcast and incorporated
	LSD $_{(0.10)}$††	11.6		87.2		5.2		
2009	0	24.6	(8.6)	12.6	(4.6)	16.9	(9.6)	with no incorporation, but disturbance#
	37,000	21.1	(5.7)	28.0	(10.0)	39.2	(38.2)	hog manure subsurface injected
	148,000	28.0	(8.0)	118.5	(78.3)	17.5	(9.6)	
	37,000	17.3	(3.2)	11.3	(0.9)	30.8	(11.8)	hog manure broadcast and incorporated
	LSD $_{(0.10)}$	6.4		25.5		14.5		

† Application rate based on wet weight
‡ Modified Kelowna extractable P
§ Standard deviations of the mean
¶ No application of manure and PAMI manure applicator coulters inserted in soil
# Least significant difference ($P \leq 0.10$)

4.4.4 Snowmelt and water run-off simulation on soil slab monoliths

Soil slab monolith samples for the thawing soil slab snowmelt portion of the study were collected at random positions within each treatment plot in mid-Oct. 2008 and mid-Oct. 2009, after harvest operations had concluded for each of those crop years in the SCM study, and in mid-Oct. 2009 after harvest operations had concluded in the 12- year long-term LHM study.

Single soil slab monolith samples for the frozen soil slab water run-off portion of the SCM study were collected in mid-Oct. 2009 after harvest operations had been completed for that crop year. Soil slab monolith samples for the frozen soil slab water run-off portion of the 12-year long-term LHM study were collected in mid-Oct. 2009 after harvest operations were complete. A single soil slab monolith was collected from each of the four replicates for every treatment in the SCM and LHM studies.

In the soil slab monolith collection process, in each treatment plot a small trench was excavated to a depth of approximately 15-20 cm in a rectangle to expose a 30 x 40 cm section of soil. A crosscut hand saw was then used to horizontally cut a 30 by 40 cm soil cross section slab at an approximate depth of 10-20 cm (Fig. 4.1). Once the soil slab section plus the accompanying crop residues had been severed from the surrounding soil, a plastic plexiglass sheet was inserted into the severed section in order to keep the slab section intact, and to ensure that the slab was not fractured during removal. The soil slab section was then wrapped in shipping tape to prevent fracture and breakup during transport to the laboratory, placed in a plastic storage container and then immediately placed in a freezer where they were stored at -20 °C until the simulated snowmelt treatment.

Fig. 4.1. Collection of soil slab monoliths from Dixon three-year solid cattle manure and 12-year long-term liquid hog manure study at Dixon, Saskatchewan.

In February of 2009 and 2010, undisturbed unblown snow that had recently (within 48 h) fallen was collected from a field at the Goodale Farm (field legal location SE4-36-4-W3) located approximately 20 km south-east of Saskatoon, SK. The undisturbed snow was collected from the field at approximately 50-100 m distance from the road to minimize any contamination of the snow from foreign roadside debris. For measuring snow melt run-off and leaching over thawing soil, the frozen soil slab monoliths were placed inside insulated plywood boxes designed to slow the rapid thawing of the soil slab so as to mimic snowmelt as it occurs in the spring, but also to allow the added snow cover to infiltrate into the subsurface of the soil and not simply run off the soil surface (Fig. 4.2). Approximately 2 kg of snow (representing 7.5 cm of snow cover in a field, equivalent to 1.67 cm of water), was added to the soil slab monolith section surface. The rear of the insulated plywood boxes was elevated to a position of five degrees to allow leachate and run-off to occur. The boxes were lined with plastic sheets to facilitate snowmelt leachate and run-off collection. Laboratory room temperature was altered for the first 48 h of the experiment to simulate spring day conditions. Specifically, temperature was altered from - 8 ˚C (night), to 0 ˚C mid-day, 5 ˚C in later portions of the day and back to -8 ˚C at night which allowed more gradual thawing of the soil slab monolith, allowing greater infiltration of the snowmelt water into the soil slab.

Fig. 4.2. Simulated snowmelt on thawing soil slab monoliths and collection of run-off-leachate.

Additionally, soil slab monoliths were used to simulate and measure nutrient movement in surface water run-off passing quickly across frozen soil. This experiment was conducted to simulate a warm Canadian prairie spring day in which snow has melted and water is moving rapidly across a field while the soil surface remains in a predominately frozen or unthawed state. A set of -20 ºC frozen soil slabs sampled from the treatments obtained in Oct. 2009 were placed in elevated boxes as described above. Two kg of water at 2 ˚C was poured over a 60-second time period from a plastic bucket directly and rapidly at a distance of 2 cm from the slab surface starting from the elevated portion of the frozen soil slab surface and water was collected at the lower portion of the elevated box as described previously.

The leachate and run-off from the thawing soil slab monoliths and the frozen soil slabs was collected, the volume collected was measured, recorded and samples immediately frozen and stored at -20 ˚C until the samples were thawed and filtered using Millipore 45 µm glass filters. All of the filtered samples were analyzed for SRP, NO_3-N and NH_4-N using a Technicon© II automated colorimetry analyzer (American Public Health Association 2005). A sub-sample of collected snow was melted separately, filtered and analyzed to determine the background levels of the above nutrients, which was subtracted from the treatment run-off concentrations.

4.4.5 Statistical analysis

Data from both the three-year SCM and 12-year long-term LHM studies were analyzed as a randomized complete block design, replicated four times for all field experiments at the SCM Saskatchewan site for SRP, NO_3-N and NH_4-N with two factors for the SCM application: rate of SCM treatment amendment and method of SCM application. The 12 year long-term LHM study was analyzed as a randomized complete block design, replicated four times for all field experiments for SRP, NO_3-N and NH_4-N with two factors for the LHM application: rate of LHM treatment amendment and method of LHM application. Data from the SCM and LHM sites were analyzed independently. Sample data was analyzed for normality and equality of variances using the univariate procedure and transformed where necessary. Means separation comparisons for all variables were conducted using the general linear model procedure using a least significant difference (LSD) of ($P \leq 0.10$) calculated with SAS Proc GLM (SAS version 9.0, 2008).

4.5 Results and Discussion

4.5.1 Soluble reactive phosphorus export in snowmelt water on thawing solid cattle manure amended soil

In the SCM soil slabs collected in the fall of 2008, the SRP exported in run-off and leachate from snowmelt was observed to be significantly ($P \leq 0.10$) higher in the broadcast and incorporated and subsurface banded treatments than the 0.02 kg P ha^{-1} exported in the unamended control (Fig. 4.3a). Soluble reactive P concentrations for fall 2008 are reported in Appendix Table B.7. As was observed in the 2008 thawing snow and soil slabs, the SRP exported in the SCM treatments in 2009 was significantly greater than the 0.03 kg SRP ha^{-1} exported in the control treatment (Fig. 4.3b). Soluble reactive P concentrations for fall 2009 are reported in Appendix Table B.8. In 2008 and 2009, the manured treatments were found to be significantly ($P \leq 0.10$) higher in SRP export than the disturbed-control treatment. Amounts of P exported in manured treatments ranged from about 0.1 kg P ha^{-1} in the broadcast SCM treatment in 2008 to about 0.5 kg P ha^{-1} in the subsurface banded treatment in 2009. The amounts of P removed from the SCM treated soils are 10 times higher than in the non-manured controls. These findings are in agreement with Smith et al. (2011) who reported that SRP concentrations in spring snowmelt water from cattle overwintering sites in east-central Saskatchewan were over 10.0 mg PO_4-P L^{-1}, which was 20 times greater than the P concentration in the control basin water run-off (0.47 mg PO_4-P L^{-1}). Olsen et al. (2010) has reported greater amounts of P and N in water runoff from cattle manured soil after the first year of application in a multi-year study in Alberta, but with reduced P and N in runoff in subsequent years. This was not the case in the present study, as the amount of SRP exported increased from 2008 to 2009, but is consistent with a greater amount of P applied in the SCM treatments in 2009 (Table 4.1) and the higher soil test extractable P in the fall of 2009 (Table 4.3).

Immobilization of P in SCM in organic forms and slow mineralization (Stumborg and Schoenau, 2008) could explain why overall SRP export was less than 1 kg SRP ha^{-1} for all three SCM application methods. As well, the brief soil-water interaction time may not have been sufficient to mobilize much P. Converse et al. (1976) and Kongoli and Bland (2002) have noted that removal of nutrients with run-off water after winter applications of manure varies with the nature of the manure. Specifically solid animal manures containing greater amounts of bedding and straw, such as the manure used in this study, can serve as a mulch platform that limits or reduces the amounts of nutrients that can be removed by snowmelt run-off water. The less than 1 kg SRP ha^{-1} export for all three SCM application methods is negligible compared to the 150 kg P ha^{-1} added in the broadcast alone, broadcast and incorporated and subsurface banded, respectively, SCM treatments in 2008. This could be accounted for by the low solubility of P in SCM and sorption to soil constituents, leading to its decreased mobility (Sharpley and Moyer, 2000). If the amount of P applied is greater than the P sorption capacity of a soil and exceeds the ability of plants to take up available supplies of P then more P is predicted to be exported by water (Brye et al., 2002), especially if there are preferential conduit modes of transport, which could explain the greater amount of SRP transported in the subsurface banded SCM treatment. The placement of SCM in a concentrated manure band could potentially overload soil mineral and organic adsorption sites which, combined with the deep horizontal banding (10-13 cm), creates more opportunity for preferential flow movement.

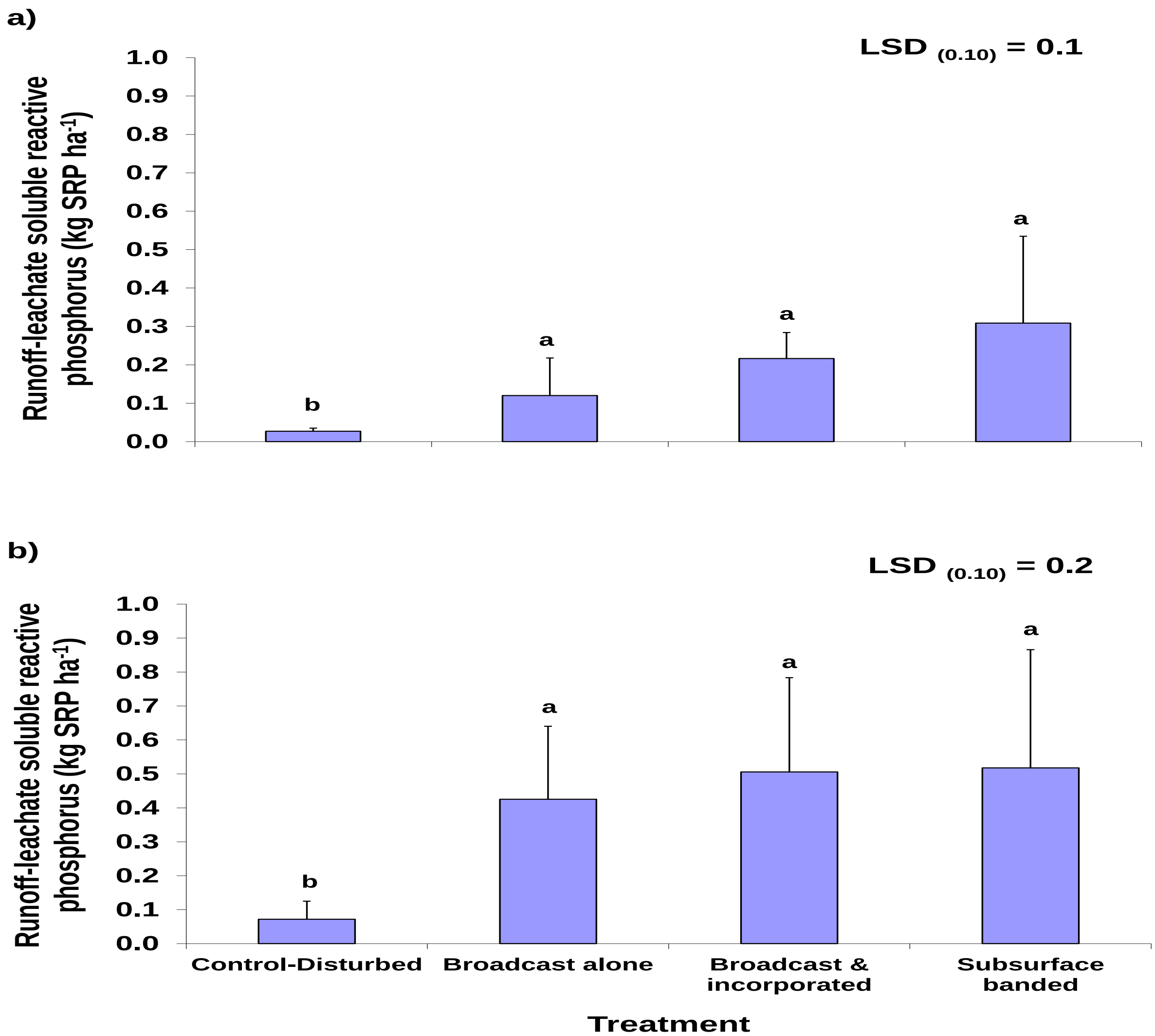

Fig. 4.3. Export of soluble reactive phosphorus (kg P ha^{-1}) by thawing snow on thawing soil slab monoliths from a three-year solid cattle manure field study collected in a) fall 2008 and b) fall 2009. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.2 Soluble reactive phosphorus export in water moving rapidly across the surface of frozen cattle manure amended soil

In snowmelt conditions of water passing rapidly over frozen soil monoliths obtained from the SCM site in mid-Oct. 2009, the SRP exported in the three manure treatments was significantly ($P \leq 0.10$) higher than the 0.03 kg SRP ha^{-1} exported in the control treatment (Figure 4.4). Soluble reactive P concentrations for fall 2009 are reported in Appendix Table B.9. Overall, SRP export in water running rapidly across the surface of SCM treatment frozen soil slabs was approximately

0.15 kg SRP ha^{-1}, which is less than one-half of that in the thawing snow and soil. This is expected due to a lower degree of interaction between water and soil when the soil surface is frozen. The longer time duration associated with the snowmelt run-off and leaching on the thawing soil slabs contrasts with the shorter time duration of the simulation of water running across the frozen surface of soil. This difference in time and frozen soil conditions which prevents infiltration of water means a reduced degree of soil-water interaction. It appears that the nature of the thaw and run-off such as thawing versus frozen soils can considerably influence the amount of nutrient ion that may be exported off the field

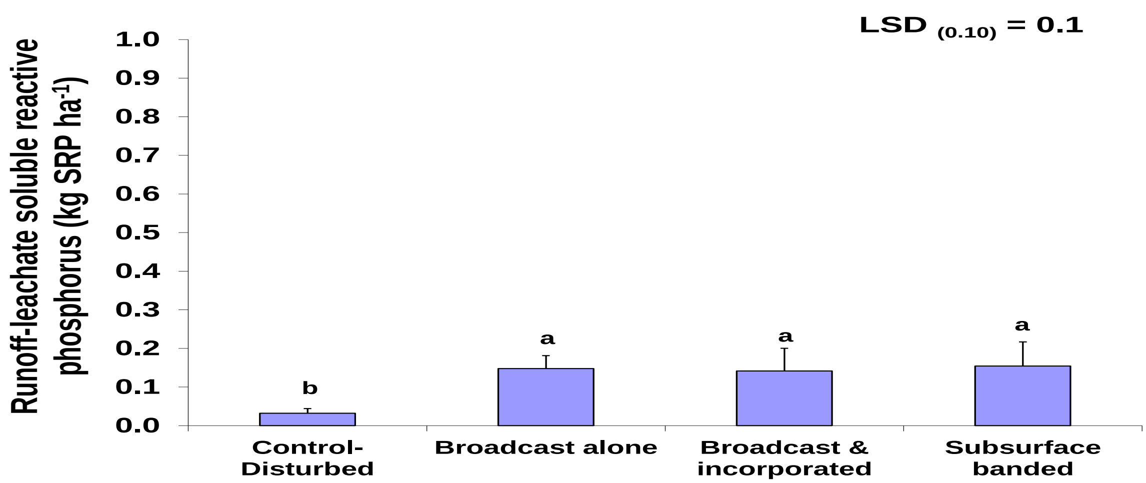

Fig. 4.4. Export of soluble reactive phosphorus (kg P ha^{-1}) in water moving rapidly across the surface of frozen soil slab monoliths collected in fall 2009 from a three-year solid cattle manure field study site. Means followed by the same letter are not significantly (P ≤ 0.10) different. Error bars denote standard deviations of the means.

4.5.3 Soluble reactive phosphorus export in thawing snow and soils from liquid hog manure amended soil

As expected, the amounts of SRP exported via run-off and leachate from thawing snow and soil slab monoliths collected from the long-term (12 years of application) LHM field study site was increased with LHM application (Fig. 4.5). The SRP removed in the annual application rate of 148,000 L ha^{-1} (Fig. 4.5) of about 0.05 kg P ha^{-1} was significantly ($P \leq 0.10$) greater than the control-disturbed treatment but was not significantly ($P \leq 0.10$) different from the other treatments, which themselves were not significantly different from the control treatment. Soluble reactive P concentrations for fall 2009 are reported in Appendix Table B.10. Overall, the LHM SRP exports from 12 years of LHM application are about 10% of the SCM exports from two years of SCM application (Fig. 4.3a), despite only slightly lower amounts of P added as LHM over 12 years in the 148,000 L ha^{-1} rate treatments as added in two years of SCM application at 60 t ha^{-1}. This can be explained in part by crop uptake and removal of the P added in the LHM treatments over the 12 years (Stumborg and Schoenau, 2008). This resulted in a smaller P surplus for the LHM field-study compared to the SCM study and much lower soil test extractable P contents in the soil of the LHM (Table 4.4) compared to the SCM (Table 4.3). The P in the LHM would have had more time to react with the soil (12 yrs application period) compared to the shorter application period in the SCM treatments (3 yrs). Campbell et al. (1984) has described how the P concentration in the soil solution is typically low and it is known that P added as fertilizer can transform into insoluble forms over time, which can retard the availability and movement of P in the soil solution. Conversion of manure P into less soluble forms may also be occurring in the LHM amended soils over the 12 years of application. The amount of P added in the LHM (Table 4.2) in Oct. 2008 and Oct. 2009 was quite low compared to the P added in the SCM (Table 4.1).

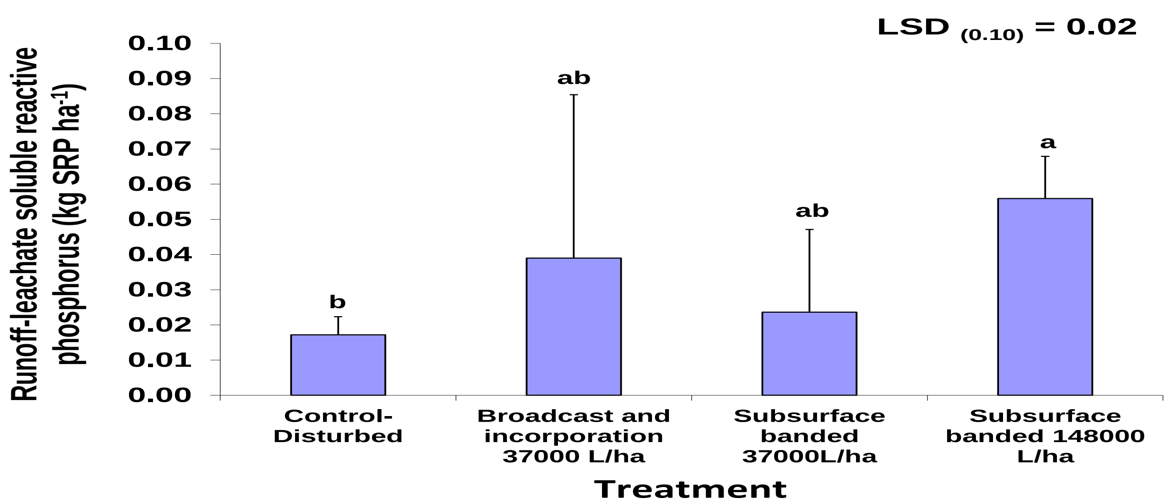

Fig. 4.5. Export of soluble reactive phosphorus (kg P ha^{-1}) by thawing snow on thawing soil slab monoliths collected in fall 2009 from a 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

Water soluble P in manure was reported by Kumaragamage et al. (2011) to be 3.4 kg t^{-1} in LHM compared to 0.8 kg t^{-1} in SCM. A greater solubility of P in LHM would be expected to result in greater amounts of exportable SRP in runoff and/or leachate from LHM amended soil compared to SCM amended per unit of P added in fresh manure. However, crop uptake and removal of labile, readily available P added over the years in the LHM treatments, low amount of P added with the LHM, along with conversion to less soluble forms once in the soil would mask any effect in the current study.

4.5.4 Phosphorus export in water moving rapidly across the surface of frozen liquid hog manure amended soil

The SRP exported in water moving rapidly across the frozen surface of the LHM soil slabs (Fig. 4.6) was approximately one-tenth of the amount of SRP export in water moving rapidly across the frozen soil surface after two years of manure application at the SCM site. This may be explained by the amount of P added, as the amount of P added over 12 years of LHM (Table 4.2) application at the 37,000 L ha $^{-1}$ rate was much smaller than the amount of P added in SCM at the 60 t ha^{-1} rate over 3 years (Table 4.1).

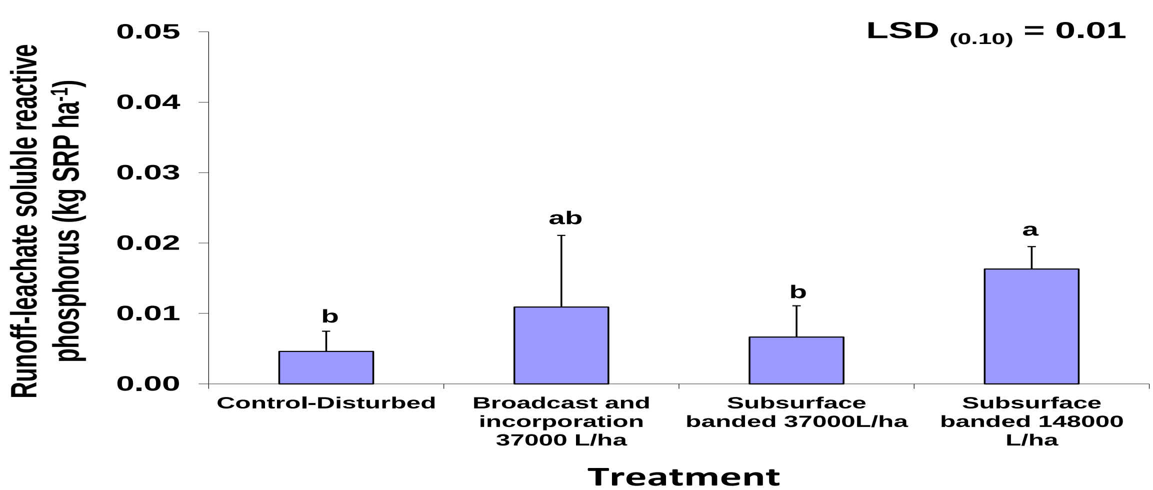

Fig. 4.6. Export of soluble reactive phosphorus (kg P ha^{-1}) in water moving rapidly across the surface of frozen soil slabs in a fall 2009 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviations of the means.

The amount of P added over 12 years of LHM (Table 4.2) application at the 148,000 L ha^{-1} rate was four times greater than the amount of P added at the 37,000 L ha $^{-1}$ rate. Soluble reactive P export was found to be much less than the SRP export in the SCM treatments. Soluble reactive P concentrations for fall 2009 are reported in Appendix Table B.11. The LHM subsurface banded high rate 148,000 l ha^{-1} produced a significantly ($P \leq 0.10$) greater amount of exported SRP in runoff moving across a frozen soil surface, compared to the lower 37,000 ha^{-1} subsurface banded LHM treatment and the control treatment. Of the different manure type (SCM and LHM) and snowmelt (thawing and frozen soil surface) scenarios examined, the rapid flow of water movement across the frozen surface of LHM amended soil resulted in the lowest SRP export from the soil, around 0.01 kg P ha^{-1}.

4.5.5 Dissolved nitrate-nitrogen export in snowmelt water on thawing solid cattle manure amended soil

In the SCM thawing soil slabs from fall of 2008, the amounts of dissolved NO_3-N in run-off and leachate snowmelt derived water were similar among manured treatments (~0.4 kg NO_3-N ha^{-1}) and were not significantly different ($P \leq 0.10$) from the control-disturbed treatment (Fig. 4.7a). Dissolved NO_3-N concentrations for fall 2008 are reported in Appendix Table B.7. This agrees with observations by Smith et al. (2011), where little NO_3-N in run-off water was observed from winter snowmelt after the first year of manure application in a winter-feeding field located in east-central Saskatchewan. Export of dissolved NO_3-N in the 2009 run-off and leachate was also similar among manured treatments (~2.0-3.0 kg NO_3-N ha^{-1}) and were not significantly different ($P \leq 0.10$) from the control-disturbed treatment (Fig. 4.7b). Dissolved NO_3-N concentrations for fall 2009 are reported in Appendix Table B.8.

Smith et al. (2011) reported average NO_3-N concentrations in water samples from cattle overwintering sites of 0.25 mg NO_3-N L^{-1} compared to 0.19 mg NO_3-N L^{-1} in control sites. The microbial conversion of organic N and NH_4-N contained in the manure to NO_3-N can be slowed by cold temperatures (Stark and Firestone, 1996), and the SCM in this study contained relatively little inorganic N. Additionally, most of the inorganic N would have been utilized by the crop in the first year after application. Moreover, the availability of N added in SCM can be very low due to cattle pen bedding material containing straw and/or wood chips, which can have a high C:N ratio, subsequently limiting mineralization and release of inorganic N (Schoenau and Davis, 2006), as discussed in Chapter 3.

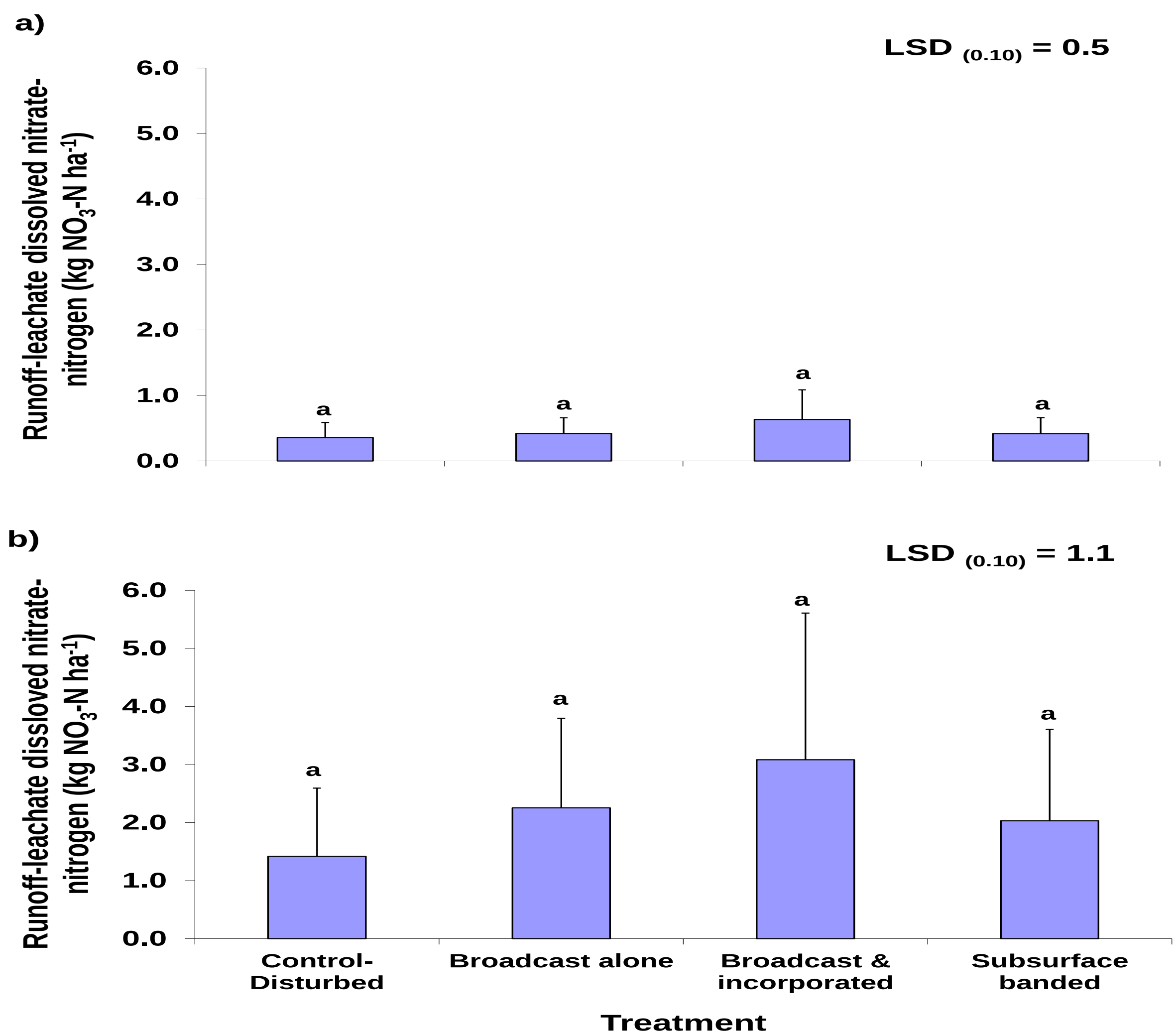

Fig. 4.7. Export of dissolved nitrate-nitrogen (kg NO_3-N ha^{-1}) by thawing snow on thawing soil slab monoliths from a three-year solid cattle manure field study collected in a) fall 2008 and b) fall 2009. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.6 Dissolved nitrate-nitrogen export in water moving rapidly across the surface of frozen solid cattle manure amended soil

Dissolved NO_3-N removal in run-off from water moving rapidly across frozen soil slab monoliths in the SCM broadcast and incorporated treatment was significantly ($P \leq 0.10$) higher than the control treatment (Fig. 4.8). Dissolved NO_3-N concentrations for fall 2009 are reported in Appendix Table B.9. The amount of nitrate removed was about half of the NO_3-N removed via snowmelt run-off and leachate in the 2008 thawing snow and soil slabs, and it was 10% of the dissolved NO_3-N removed in the 2009 thawing snow and soil slabs (Fig. 4.7b).

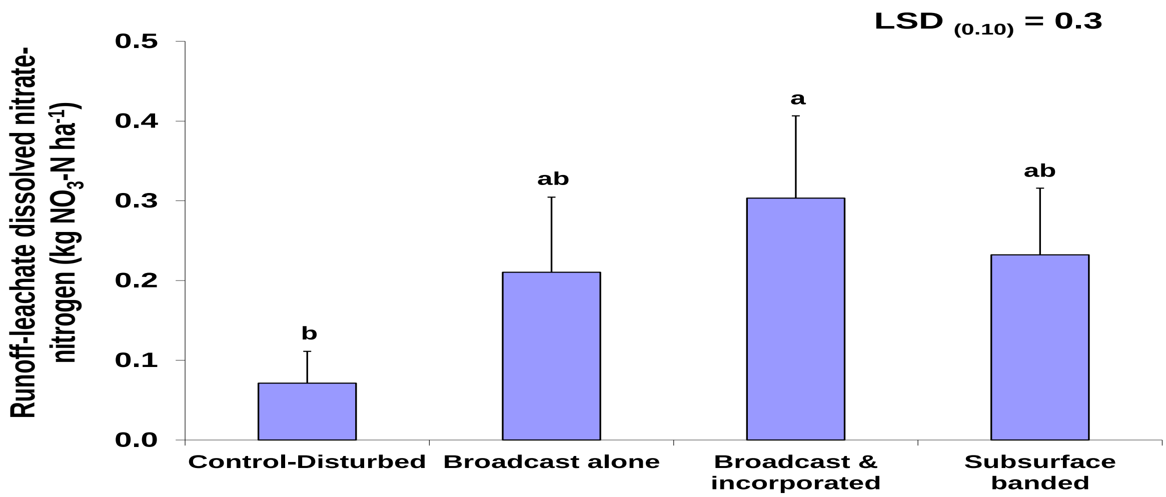

Fig. 4.8. Export of dissolved nitrate-nitrogen (kg NO_3-N ha^{-1}) in water moving rapidly across the surface of frozen soil slab monoliths collected in fall 2009 from a three-year solid cattle manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.7 Dissolved nitrate-nitrogen export in snowmelt water on thawing liquid hog manure amended soil

There were no significant ($P \leq 0.10$) differences in dissolved NO_3-N export in water from thawing snow and soil slab monoliths collected in fall of 2009 among the three treatments and the non-manured control (Fig. 4.9). Dissolved NO_3-N concentrations for fall 2009 are reported in Appendix Table B.10. For the low rate of application, the subsurface banding tended to result in greater export than broadcast and incorporate, and export increased with rate. The amounts removed (about 1-4 kg NO_3-N ha^{-1}) were similar to the amounts of nitrate removed in the SCM fall 2009 soils, despite lower fall soil nitrate contents in the SCM amended soils compared to the LHM amended soils. The reason for this is not known, but might reflect a greater interaction of snowmelt water with the soil in the SCM amended soil compared to the LHM amended soil.

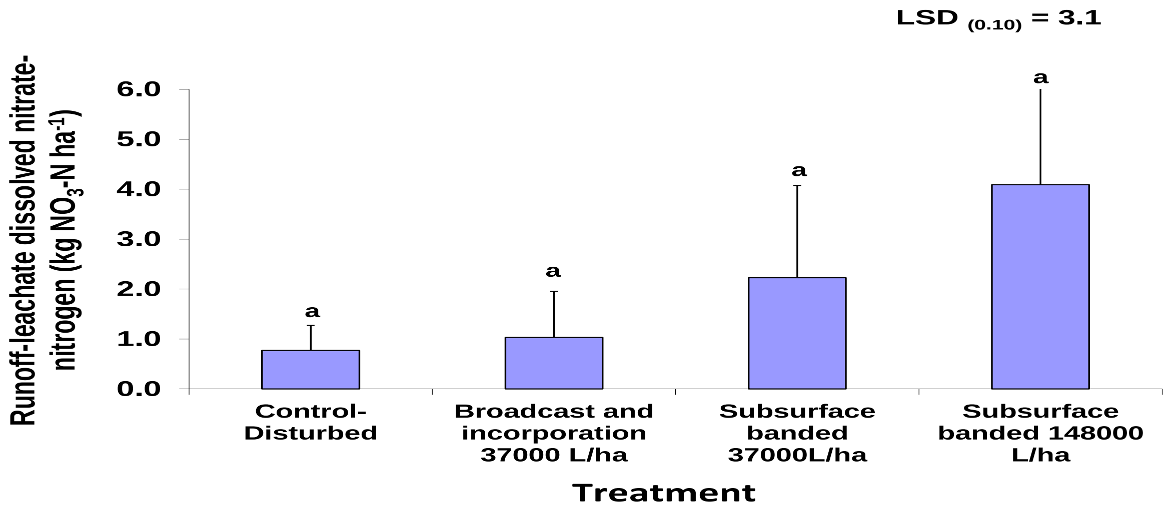

Fig. 4.9. Export of dissolved nitrate-nitrogen (kg NO_3-N ha^{-1}) by thawing snow on thawing soil slabs collected in fall 2009 from a 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.8 Dissolved nitrate-nitrogen in water moving rapidly across the surface of frozen liquid hog manure amended soil

Dissolved NO_3-N export in water passing over frozen soil slab monoliths was not significantly different among the LHM treatments (Fig. 4.10). Dissolved NO_3-N concentrations for fall 2009 are reported in Appendix Table B.11. As for phosphate, amounts of NO_3-N removed in water passing over the frozen surface were considerably less than for snow melting on thawing soil. Soil texture, water infiltration rates and redistribution of crop residues via tillage operations can all have an effect on the amount of NO_3-N that is retained near the soil surface (Stumborg et al., 2007). The subsurface flow of snowmelt water through thawing soil often results in much greater NO_3-N removal (Li et al., 2011).

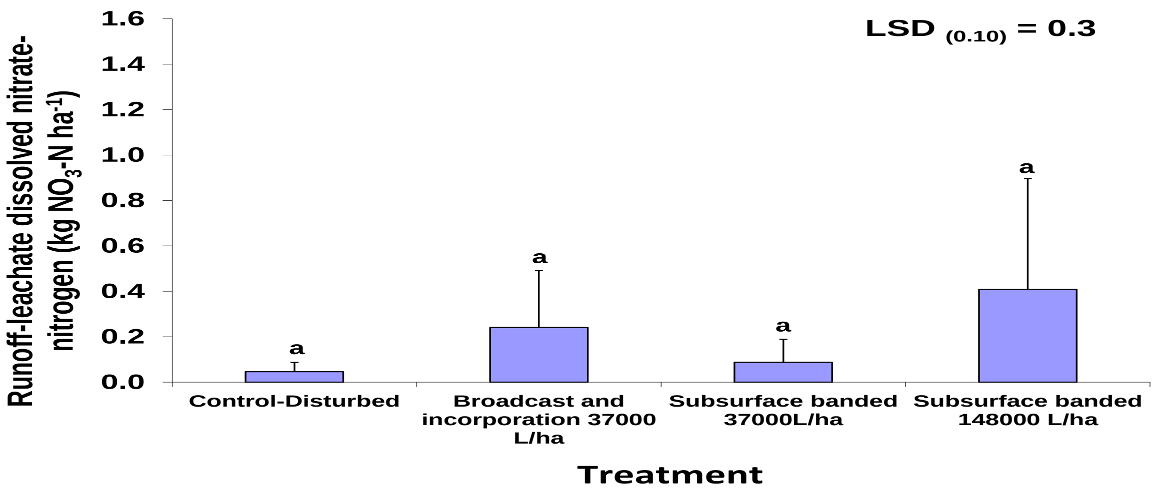

Fig. 4.10. Export of dissolved nitrate-nitrogen (kg NO_3-N ha^{-1}) in water moving rapidly across the surface of frozen soil slabs in a fall 2009 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviations of the means.

4.5.9 Dissolved ammonium-nitrogen export in snowmelt water on thawing solid cattle manure amended soil

The dissolved NH_4-N export was not significantly ($P \leq 0.10$) different between the disturbed-control treatment, broadcast alone, broadcast and incorporated and subsurface banded SCM treatments (Fig. 4.11). Strong adsorption to soil particles could explain the low amount of NH_4-N extracted by water passing across and through the soil. Manure NH_4-N is readily adsorbed and held on the soil cation-exchange sites and is not easily extracted from the soil with water. In this study, the NH_4-N released from manure could also have been rapidly utilized by plants during the growing season and/or nitrified thus leaving little residual NH_4-N (Stumborg et al., 2007). In agreement with this, soil NH_4-N contents in the fall were low (Table 4.3), and are consistent with low (around 0.02 kg NH_4-N ha^{-1}) amounts of NH_4-N exported in the run-off and leachate water collected from the melting snow on the slabs. The amounts of NH_4-N exported are about 50 times lower than the amounts of NO_3-N (Fig. 4.10). Dissolved NH_4-N concentrations for fall 2008 and fall 2009 are reported in Appendix Tables B.7 and B.8.

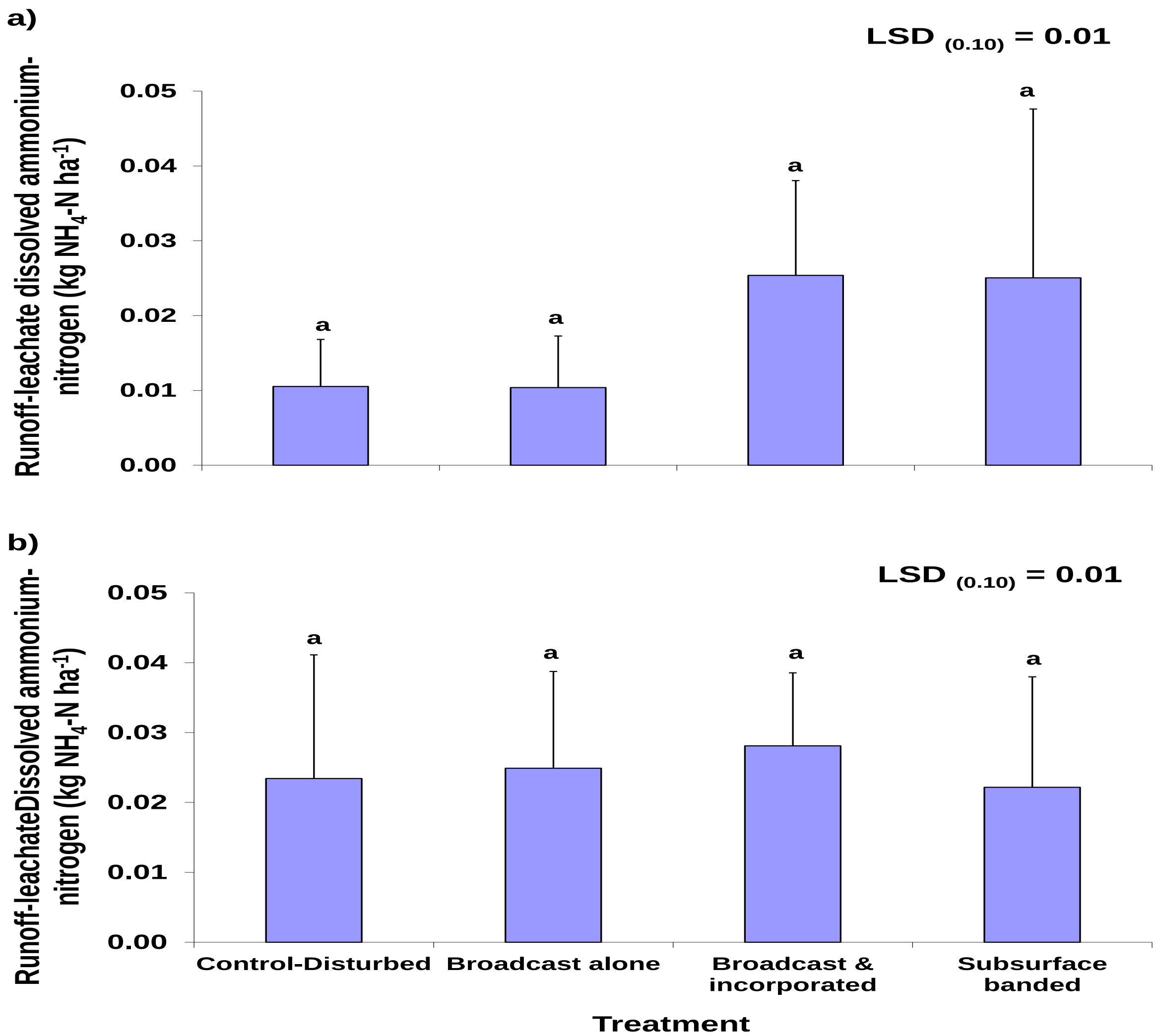

Fig. 4.11. Export of dissolved ammonium-nitrogen (kg NH_4-N ha^{-1}) by thawing snow on thawing soil slab monoliths from a three-year solid cattle manure field study collected in a) fall 2008 and b) fall 2009. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.10 Dissolved ammonium-nitrogen export in water moving rapidly across the surface of frozen solid cattle manure amended soil

The manure treatments and nature of run-off had relatively little effect on NH_4-N export in water running rapidly across a frozen soil surface in this study (Fig. 4.12). Dissolved NH_4-N concentrations for fall 2009 are reported in Appendix Table B.9. The NH_4-N is bound to soil colloids, which limits its interaction and release to water passing through. The frozen condition of the surface soil would further limit interaction. However, others have noted that NH_4-N export can still occur depending on ice content in the pores (Steenhuis et al., 1981).

As noted previously, there was very little NH_4-N added with the SCM, which could also account for the small amount of run-off and leachate NH_4-N. In 2009, NH_4-N exports were not enhanced in manure treatments compared to the control treatment. Infiltration of the soil micropores by water from snowmelt can be prevented if ice content is blocking the pore system (Ginting et al., 1998; Zuzel and Pikul, 1987). Given the low NH_4-N content in soils receiving SCM as a consequence of plant uptake and rapid nitrification, and the retention by adsorption to clays and OM, it is not surprising that the manure treatment had minimal influence on NH_4-N export (Fig. 4.12), and there was little difference in export on thawing and frozen soils.

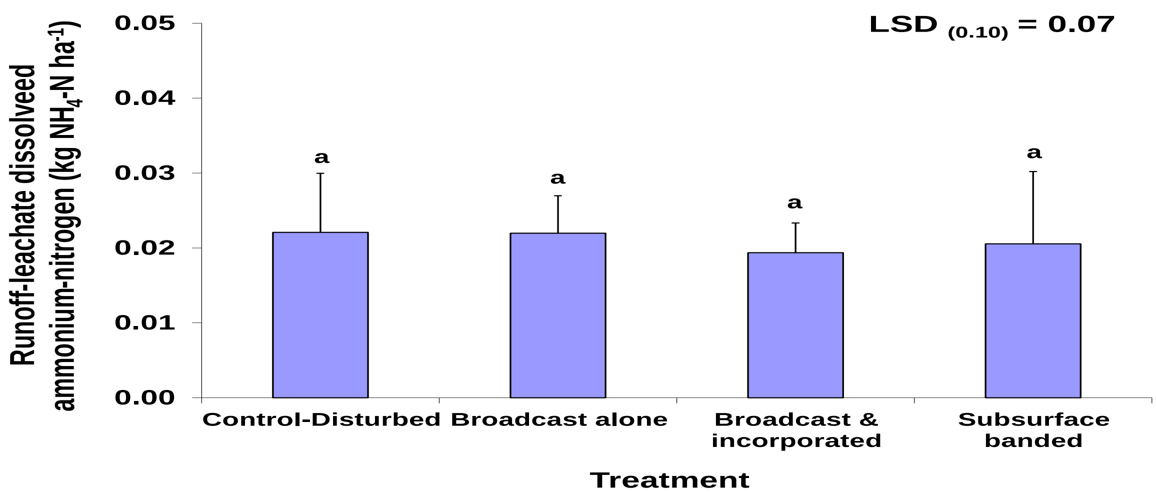

Fig. 4.12. Export of dissolved ammonium-nitrogen (kg NH_4-N ha^{-1}) in water moving rapidly across the surface of frozen soil slab monoliths collected in fall 2009 from a three-year solid cattle manure field study site. Means followed by the same letter are not significantly ($P \leq$ 0.10) different. Error bars denote standard deviations of the means.

4.5.11 Dissolved ammonium-nitrogen export in snowmelt water on thawing liquid hog manure amended soil

There were no significant differences in NH_4-N export in water among the three LHM treatments at the 12-year long-term site (Fig. 4.13). Dissolved NH_4-N concentrations for fall 2009 are reported in Appendix Table B.10. With similar clay content at both the SCM and LHM field sites (they are located adjacent to each other), cation adsorption would be similar. More NH_4-N was added with the LHM compared to the SCM, however run-off and leachate NH_4-N concentrations were similar, which could be attributed to utilization of the LHM NH_4-N by the crops along with nitrification from the time of application in spring to sampling time in the fall.

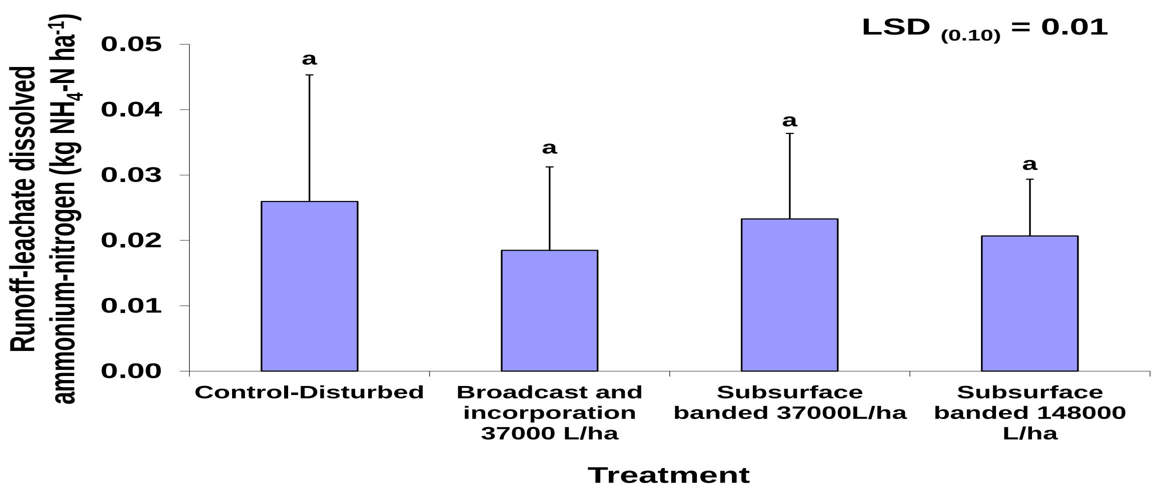

Fig. 4.13. Export of dissolved ammonium-nitrogen (kg NH_4-N ha^{-1}) by thawing snow on thawing soil slabs collected in fall 2009 from a 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars denote standard deviations of the means.

4.5.12 Dissolved ammonium-nitrogen in water moving rapidly across the surface of frozen soils from liquid hog manure amended soil

Similar to the results from the SCM treatments, the amount of NH_4-N exported in all three of the LHM treatments for water running across frozen soils was similar and not significantly ($P \leq 0.10$) different from the control treatment (Fig. 4.14), and also similar to the amount of NH_4-N collected in run-off and leachate from thawing snow and soil slabs (Fig. 4.13). Dissolved NH_4-N concentrations for fall 2009 are reported in Appendix Table B.11. The lack of treatment effects of LHM on NH_4-N export is similar to the lack of treatment effects for SCM. There was less NH_4-N added in the SCM compared to the NH_4-N added in the LHM. The observed lack of difference among LHM treatments may be attributed to the rapid conversion of NH_4-N to NO_3-N in the nitrification process following manure application and over the subsequent growing seasons, leaving little N accumulated in the soil as NH_4-N by the time of slab removal after harvest in the fall. Also, any residual removal of NH_4-N by water could be reduced due to retention of NH_4-N on soil cation exchange sites.

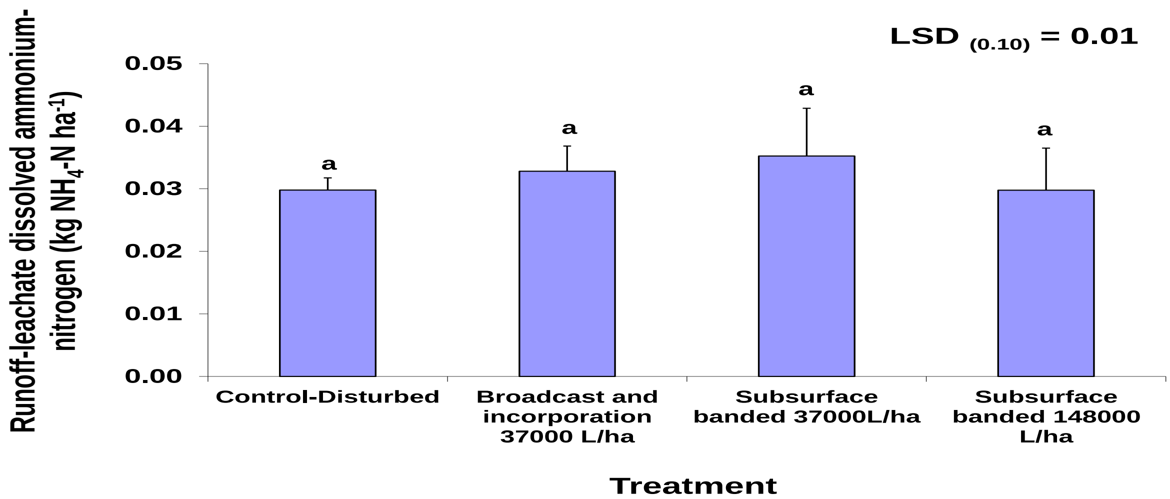

Fig. 4.14. Export of dissolved ammonium-nitrogen (kg NH_4-N ha^{-1}) in water moving rapidly across the surface of frozen soil slabs in a fall 2009 12-year long-term liquid hog manure field study site. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviations of the means.

4.6 Conclusion

The addition of SCM using broadcast alone, broadcast and incorporated and subsurface banding techniques significantly increased SRP export in thawing snow and soil slab monoliths. However, there was no significant ($P \leq 0.10$) effect of SCM placement method on SRP export in snowmelt run-off and leachate in the soil slabs obtained from the SCM treated plots. This suggests that incorporation of manure or subsurface banding may not be effective in reducing transport. While in-soil placement may reduce manure contact with water during spring melt, it may also enhance the process of manure decomposition and production of SRP as well as provide channels for preferential flow of water. The addition of SCM using all three placement methodologies significantly increased SRP export in run-off collected from water flowing rapidly across the frozen surface of a soil slab. However, the amounts exported by water running across frozen soil were about one half of that exported from snowmelt running off and percolating through thawing soil. Compared to three years of SCM application, applying LHM for 12-years resulted in smaller amounts (about ten times less) of SRP exported in water from soil slab monoliths. This may be explained by crop removal and lower manure P input over the duration of the 12-year long-term LHM study. Reduction in the solubility of the P with aging could also be a factor. Chemical and spectroscopic assessments of phosphorus species present in the soils would help confirm this aspect.

There was no significant effect of manure application rate or method on NO_3-N export, except for the broadcast and incorporate SCM treatment which had higher NO_3-N export in water flowing across the frozen soil surface compared to the unamended control. Overall greater variability was encountered in NO_3-N export compared to SRP. Similar to phosphate export, the NO_3-N export was lower in water running across frozen soil surfaces compared to snowmelt occurring on thawing soils. Interestingly, NO_3-N export was similar between SCM and LHM amended soils, despite the LHM soils having higher NO_3-N content. There was a trend for the high LHM application rate which caused accumulation of NO_3-N in the soil to have the highest NO_3-N export in snowmelt water. Manure treatment had no significant ($P \leq 0.10$) effect on NH_4-N export in the soils, regardless of type of applied animal manure. This may be attributed to the predominance of NO_3-N over NH_4-N, likely due to rapid nitrification of the NH_4-N, especially after several years of manure application. Nitrification, N uptake by the crop, and adsorption of NH_4-N to soil cation exchange sites could explain the observed small amounts of NH_4-N removed by water in the manure treatments.

5. EFFECT OF SOLID CATTLE MANURE PLACEMENT METHOD ON SOIL CARBON, PHOSPHORUS AND NITROGEN REMOVAL BY LEACHING IN INTACT SOIL CORES

5.1 Preface

The application of animal manures to agricultural soil is a common method of returning phosphorus (P) and nitrogen (N) that is removed from fields via plant uptake and harvest, and subsequently consumed by animals. Upon incorporation into the soil through tillage and/or seeding operations, microbial breakdown and solubilization of nutrient-containing manure constituents can serve as a P and N nutrient source for plants and build soil organic matter. Nutrient movement offsite from run-off and/or leaching can lead to non-point source contamination of surface and subsurface water bodies. Chapter 4 covered a series of experiments in which soluble reactive inorganic P and inorganic N transport was assessed in simulated snowmelt run-off from manure amended soils. This chapter (Chapter 5) covers a study in which the vertical transport of organic and inorganic forms of nutrient was assessed in manure amended soils. This was accomplished via the collection of intact soil cores from manured field plots followed by collection of leachate from the bottom of the cores. In this study, cattle manure treatments were utilized and because of the dominant presence of organically bound N for cattle manure identified in Chapters 3 and 4, both organic and inorganic forms of carbon (C) and N were measured along with phosphate and nitrate in the leachate.

5.2 Abstract

Spring snowmelt in Saskatchewan can transport nutrients such as phosphorus (P) and nitrogen (N) from the soil surface as well as leach nutrients situated on the soil surface or upper surface (0-5 cm depth) downward in the soil profile. Rainfall events during the spring and summer can also induce net downward leaching. The objective of this study was to determine how the placement of solid cattle manure (SCM) affects the export of total organic carbon (TOC), total N, orthophosphate (PO_4-P) and nitrate-nitrogen (NO_3-N) from the surface via downward leaching in the soil profile using intact soil columns (0-15 cm) collected from manured plots in the field. Treatments in which the SCM was applied using the subsurface banded application method showed greater export of all nutrients compared to the SCM broadcast alone treatment. Total OC export during the first leaching event in the subsurface banded high rate (60.6 t ha^{-1}) SCM treatment was 13.5 kg C ha^{-1} and was about double the export (6.4 and 7.6 kg C ha^{-1}) in the broadcast alone and broadcast and incorporated treatments, respectively. Total N export out of the core in the subsurface banded treatment was 3.5 and 3.9 kg total N ha^{-1} after the first and second soil core leaching, and was significantly higher than the total N leached in the broadcast alone and broadcast and incorporated treatments. Orthophosphate-P leached out of the intact soil cores from the subsurface banded treatment was 1.9 kg P ha^{-1} during the first leaching event and was significantly greater than the orthophosphate-P leached out of the broadcast alone and broadcast and incorporated SCM treatments. A higher content of soluble P forms at depth in the soil such as originating from a residual band of manure could explain the greater amount of P removed from the 0-15 cm depth in the subsurface banded SCM treatment, compared to the other two SCM treatments. Nitrate-N exported from the soil core was greater in the subsurface banded (0.93 kg NO_3-N ha^{-1}) and broadcast and incorporated (0.92 kg NO_3-N ha^{-1}) SCM treatments, compared to broadcast alone treatment. Subsurface banding of SCM at the 10-13 cm depth would decrease the contact with soil mineral and organic adsorption sites and also potentially increase microbial decomposition and mineralization compared to broadcasting, allowing for greater element leaching from the surface horizons.

5.3 Introduction

The downward transport from the surface following high rates of manure application can serve as a nutrient input to subsoil horizons (Ashjaei et al., 2010), affecting transformations and fate of nutrient in both the surface and subsurface horizons. Phosphorus that is transported to surface and subsurface water bodies can cause environmental problems such as eutrophication, while contamination from N can cause human health problems. The water passing through the soil, termed leachate, may flow laterally or vertically. Export in surface run-off and shallow subsurface lateral flow from simulated snowmelt conditions was examined in the previous chapter (Chapter 4). Due to the higher amount of N in the organic form in SCM and the C content present in the SCM fecal matter and straw bedding, the amount of N released through mineralization can be quite low, especially in the year of SCM application (Qian and Schoenau, 2002b). Beef cattle feedlot manure contains about ~15 % C and adds considerable amounts of organic matter (OM) to the soil (Eghball and Gilley, 1999), and a portion of this C is mobile in water and can potentially affect transformations of P and N in the subsoil (Konschu, 2013). Therefore, it is also important to consider C in leachate water. Depending on spring time soil moisture and temperature conditions, NO_3-N can be exported from a field site by surface runoff and/or subsurface downward leaching movement (Karamanos et al., 2007).

In the soil itself, phosphorus (P) is thought to be a relatively immobile nutrient, due to the ability of the soil to remove P from solution and retain the phosphate ion via adsorption and precipitation reactions (Haygarth and Jarvis, 1999). Solid cattle manure contains P in both organic and inorganic forms. Soil nutrients released from applied animal manure are subject to off-field export via surface run-off water and subsurface leachate from melting snow, as well as rainfall events (Chanasyk and Woytowich, 1987; McConkey et al., 1997; Van Vliet and Hall, 1991). Depending on soil moisture and temperature conditions during spring snowmelt, organic P can be mobilized and mineralized, and is rendered available for leaching export (Sims and Sharpley, 2005). The amount of P that can be leached in soil from SCM is greater if the soil has a higher available soil P content (Ashjaei et al., 2010) and if the soil has received large amounts of SCM and/or received SCM for a long time period (Eghball et al., 1996). Ashjaei et al. (2010) reported that after eight years of 400 kg N ha^{-1} SCM application rates, water soluble P removed in soil columns by leaching was significantly greater than unamended controls. Eghball (2003) observed in a Nebraska soil that when SCM was applied on a crop N requirement basis, P accumulated in the upper 15 cm and more leaching of P was observed at a 30 cm depth.

Along with affecting P transport in water moving overland, the overloading of P sorption sites seems likely to allow non-sorbed P to move downward from the surface horizon in the soil profile with percolating water from annual events such as spring snowmelt in the Canadian prairies, as well as intense rainfall events throughout the season. Nitrate-N leaching in soil receiving SCM is dependent on the composition of the manure N and environmental conditions. Nitrogen in manure that is in either an organic form or NH_4-N will not be highly mobile (Ashjaei et al., 2010). In SCM, most of the N is comprised of organic N, with small amounts of NH_4-N and little or no NO_3-N (see Chapter 3). Nitrate is the soluble, most mobile form of N. The degree of mineralization and nitrification of NH_4-N to NO_3-N, enhanced by warm, moist soil conditions, will greatly influence the overall leaching potential of N added to soils in SCM (Eghball and Power, 1999). The fate of soluble P and N will also be affected by OC in the soil solution, as it is a readily decomposable substrate for promoting microbial growth and transformations.

In Chapter 4, the effect of manure placement on the horizontal surface and lateral subsurface transport of reactive inorganic PO_4-P, NO_3-N and NH_4-N by snowmelt water was detailed. These ions were investigated because of their direct and immediate importance as sources of nutrient for aquatic growth organism such as algae when entering into surface water bodies directly from run-off. However, water passing through soil has a greater opportunity to interact with the soil and remove other forms of nutrients important in cycling, especially in cattle manure amended soils which add considerable amounts of OM directly to the mineral soil when incorporated or banded. Previous studies have examined leaching processes in soil using columns of soil that are made by packing with dried and ground soil removed from the field, it was felt that use of this approach in this study would create too many artifacts (Tarkalson and Leytem, 2009; Ojekami et al., 2011). The mobility of P and N forms from application of high rates of SCM application as affected by method of application (e.g., broadcast alone versus broadcast and incorporated versus subsurface banded application methods) has not been documented, yet is important when making decisions for best placement of manure to maximize plant recovery and minimize losses.

Therefore in this study the approach was to use intact soil cores collected directly from the field soil so as to preserve the crop residue and manure distribution as well as the soil macro and micro structure that is important in water flow through the soil and interaction of the water with the soil. One consideration of the soil core method is that it is an indirect measurement of soil NO_3-N leaching from the surface (0-15 cm) depth. The leaching is time dependent and spatially variable caused by varying N concentrations in SCM and factors controlling rates of mineralization and distribution in broadcast alone, broadcast and incorporated and subsurface banded application methodologies. In-situ approaches to leaching assessment like lysimeters may not be most appropriate for manure placement studies with high anticipated variability across the plot area such as this, due to the large number of units that may be required to be installed per plot. The objective of this experiment was to collect intact soil cores and conduct leaching assessments to determine how the placement of SCM in broadcast alone, broadcast and incorporated and subsurface banded methods affects the leaching of soluble organic C and N, along with PO_4-P and NO_3-N in the top layer of the soil.

5.4 Materials and Methods

5.4.1 General experimental setup

A detailed description of the Dixon SCM field study site was previously provided in Chapter 3, specifically, section 3.4.2. The SCM field trial soil core leaching study was set up as a randomized complete block design, and treatments were replicated four times. The Dixon site was established in the spring of 2007 when SCM was applied to the plots measuring 3.05 x 6.09 m. There are two control treatments for the SCM trial at Dixon, the first consisting of no manure or fertilizer being applied and no disturbance of the soil (unamended, undisturbed control), the second control treatment consisting of no manure or fertilizer being applied but with disturbance of the soil using the coulter openers of the SCM injector machine. Solid cattle manure was applied using three application procedures; 1) broadcast application where SCM was applied on the soil surface (no incorporation), 2) broadcast and incorporated where SCM is applied on the soil surface and then incorporated using a disk, 3) subsurface injection, where SCM is subsurface banded using the PAMI SCM Injector Machine in six subsurface trenches using 60 cm coulter openers spaced 30 cm apart, applying SCM product at a depth of 10-13 cm. Closing wheels of 45 cm diameter covered the exposed injection trench containing the manure with soil.

5.4.2 Core collection and leaching experiment

The experimental site description and manure treatments at Dixon, SK used for this experiment are described in section 3.4 of this thesis and will not be repeated here. Three intact soil cores were removed from each of the four replicate plots of the disturbed-control treatment, broadcast alone, broadcast and incorporated and subsurface banded SCM manure treatments. Intact soil cores were collected from the experimental treatment plots using polyvinyl chloride (PVC) pipe tubes measuring 10.0 cm inside diameter by 15.0 cm in overall length were inserted into each of the four high SCM rate (60.6 t ha^{-1}) replicate plots, applied as 1) broadcast alone, 2) broadcast and incorporated, and 3) subsurface banded application of manure completed in May of 2007. The intact soil cores were inserted to a depth of 15 cm and collected using a hand held core pounder device in mid-Oct. 2007, after harvest operations on the field site had been completed. Three cores were collected from each plot at random. The intact soil PVC pipe, with accompanying surface crop residues were excavated, placed in plastic bags and frozen at -20 °C to represent winter conditions.

For the leaching study, the frozen cores were first removed from the freezer and allowed to slowly thaw and warm to 20 ^{o}C. A leaching system was developed and is described as follows. To enable collection of the leachate from the intact soil PVC cores, the bottom of the intact soil cores was covered with perforated washed cloth screen. The cloth was pre-washed and rinsed with deionized water four times beforehand and used to prevent any particulate material that might be loosened from the bottom of the core from entering into the leachate collection vessel (Fig. 5.1). Another PVC core was placed on top of the soil PVC core with the seam wrapped in parafilm and duct taped to prevent water leakage. All core were brought to field capacity by adding 200 ml of deionized water and then allowed to equilibrate for 48 hours. Any small amount of excess water that was noted to have leached through the soil cores during this period were collected and poured back onto the core. Once field capacity was achieved and the core had equilibrated, two separate leaching operations was conducted. In each leaching event, the intact soil cores were leached with 392 ml of deionized water, added to the surface representing a 5 cm leaching event, calculated using the volume and core diameter of the cylinder. After one week, another 392 ml of deionized water was added to the soil cores. All leachate water was collected over a 24 h period and measured, with evaporation prevented by covering the collection vessel with plastic. The leachate water was immediately frozen and stored in a freezer at -20 $^{\circ}$C until analysis. After thawing to 20

^{o}C, samples were filtered by passing the leachate volume through Millipore^{TM} 45 µm glass filters. The filtered samples were then immediately analyzed for: total organic carbon (TOC) and total N using a Shimadzu TOC-V analyzer. The NH_4-N, NO_3-N and orthophosphate P (soluble reactive P; SRP) were measured colorimetrically using a using a Technicon™ automated colorimetry analyzer as described in Chapter 4.

Fig. 5.1. Photograph depicting intact soil core leaching experiment.

5.4.3 Statistical analysis

Data were analyzed as a randomized complete block design, replicated four times using three samples collected per treatment for all field experiments at the SCM Saskatchewan site for TOC, TN, orthophosphate-P and NO_3-N and NH_4-N with one factor for the method of SCM application. Sample data was analyzed for normality and equality of variances using the univariate procedure and log transformed where necessary. Means separation comparisons for all variables were conducted using the general linear model procedure using a least significant difference (LSD) ($P \leq 0.10$) calculated with SAS Proc GLM (SAS version 9.0, 2008).

5.5 Results and Discussion

5.5.1 Total organic carbon and nitrogen

Total organic C measured in water leachate samples from the subsurface banded high SCM rate (60 t ha^{-1}) treatment plots had significantly higher ($P \leq 0.10$) TOC content than the broadcast alone and broadcast and incorporated SCM manure treatments (Fig. 5.2). Both the first and second leaching TOC amounts for the subsurface banded treatment have greater variability in the results. This could be attributed to greater sampling variability on a microscale (i.e., cm or m) in the field created by the SCM subsurface banding in the 10-13 cm depth. Soil OC ranged from 2.2 to 2.9 % C by weight at the site used for the three year SCM study (Table 3.6).

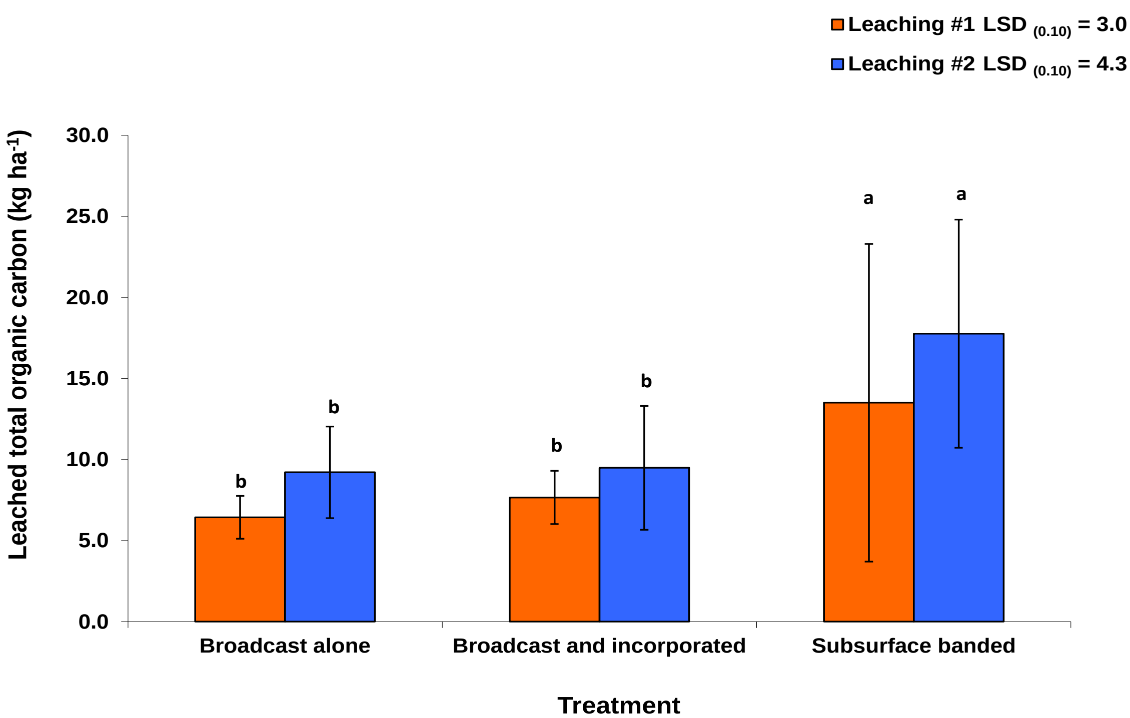

Fig. 5.2. Total organic carbon removed from intact soil cores receiving two, 5-cm leaching events. Treatments evaluated are a high cattle manure application rate (60 t ha^{-1}) applied using different application methods: broadcast, broadcast and incorporate and sub-surface banding. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviation of the mean.

Total OC export of 13.5 kg C ha^{-1} soil through the bottom of the core in the first leaching of the subsurface banded treatment cores was about double the export of 6.4 and 7.6 kg C ha^{-1} in the broadcast alone and broadcast and incorporated SCM treatments, respectively. As a 2.2 % soil OC concentration would correspond to about 40,000 kg OC per hectare in the 0-15 cm depth, the export of organic C in the leachate of 5 to 15 kg C ha^{-1} is insignificant compared to the total soil OC pool. After a second leaching event was imposed on the intact soil cores, the subsurface banded SCM treatment was also found to result in greater levels of TOC export than either the broadcast alone and broadcast and incorporated SCM treatments (Fig. 5.2).

Total N that was leached from intact soil cores in the subsurface banded high SCM rate (60.6 t ha^{-1}) treatment plots was 3.5 and 3.9 kg total N ha^{-1} during the first and second leaching, respectively. This was significantly greater than the broadcast alone and broadcast and incorporated treatments (Fig. 5.3), following the same pattern as OC. This is expected, as OC and N in manure are closely related, although the C:N ratio may vary somewhat depending on source and degree of decomposition (Qian and Schoenau, 2002).

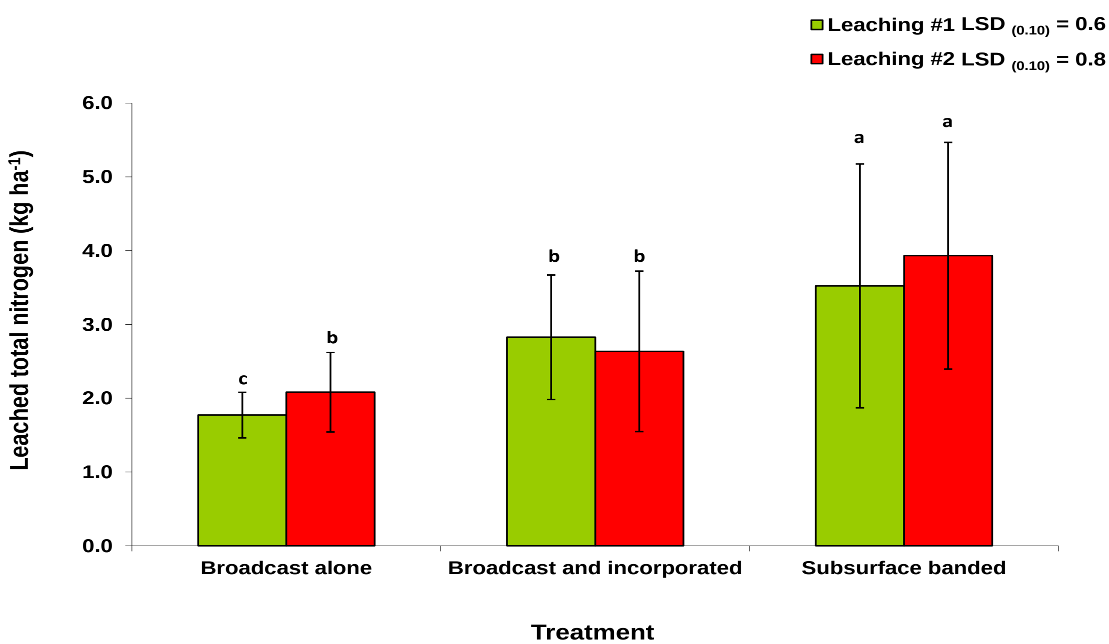

Fig. 5.3. Total nitrogen removed from intact soil cores receiving two, 5-cm leaching events. Treatments evaluated are a high cattle manure application rate (60 t ha^{-1}) applied using different application methods: broadcast, broadcast and incorporate, and sub-surface banding. Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviation of the mean.

The C:N ratio calculated using organic C and estimated organic N (total N – NO_3-N) content of the leachate is about 5:1 or less, suggesting that the OM leached would result in net mineralization when decomposed. The sustained removal of OC and N in the second leaching event compared to the first suggests continued mobilization of soluble OM in all the manured soil treatments.

Overall, subsurface placement through incorporation and especially subsurface banding of the SCM resulted in more organic C and N removed from the 0-15 cm depth. This may be explained by a lower degree of interaction between the subsurface banded manure with soil constituents like clays that can fix manure OM through adsorption processes. The banded manure is placed at a lower depth (~10-13 cm), and could potentially provide a lower opportunity for the manure to interact with the soil before it leaves the bottom of the column with the water. Seeding operations could mix the broadcast and alone and broadcast and incorporated SCM with the mineral and other organic soil constituents to a lower soil depth, however, likely not as deep as the 10-15 cm placed subsurface banded SCM. In-soil manure placement may also enhance microbial activity and the production of soluble organic that can be transported downward with water (Charles, 1997). The effect of subsurface banding leading to less fixation of fertilizer nutrients, especially P, compared to broadcast and incorporation is well established (Havlin et al., 2014). Transport of OC and N from surface to subsurface horizons with percolating water is likely to influence the transformations of this manure derived OM (Konschuh, 2013). For example, rates of mineralization may be altered by cooler temperatures and a different microbial population at depth.

It is important to note that the SCM in this study was applied in the spring prior to seeding operations. The SCM broadcast alone, broadcast and incorporated and subsurface banded treatments all had some soil disturbance associated with the seeding operation, as the seeding tool used sweeps as openers. Consequently, even the manure in the broadcast alone treatment would have had some incorporation into the soil, although not as much as the broadcast and incorporation and the subsurface banded treatments.

5.5.2 Orthophosphate-phosphorus and nitrate-nitrogen

The estimated leaching of orthophosphate-P in the subsurface banded 60.6 t ha^{-1} SCM manure application treatment cores was calculated to be 1.9 kg P ha^{-1} in the first leaching and was significantly greater ($P \leq 0.10$) than the broadcast and incorporated treatment (Fig. 5.4). Similarly, with the second leaching event, the subsurface banded SCM treatment P soil core had greater leaching compared to the broadcast alone and broadcast and incorporated SCM treatments but the difference was not significant among placement methods.

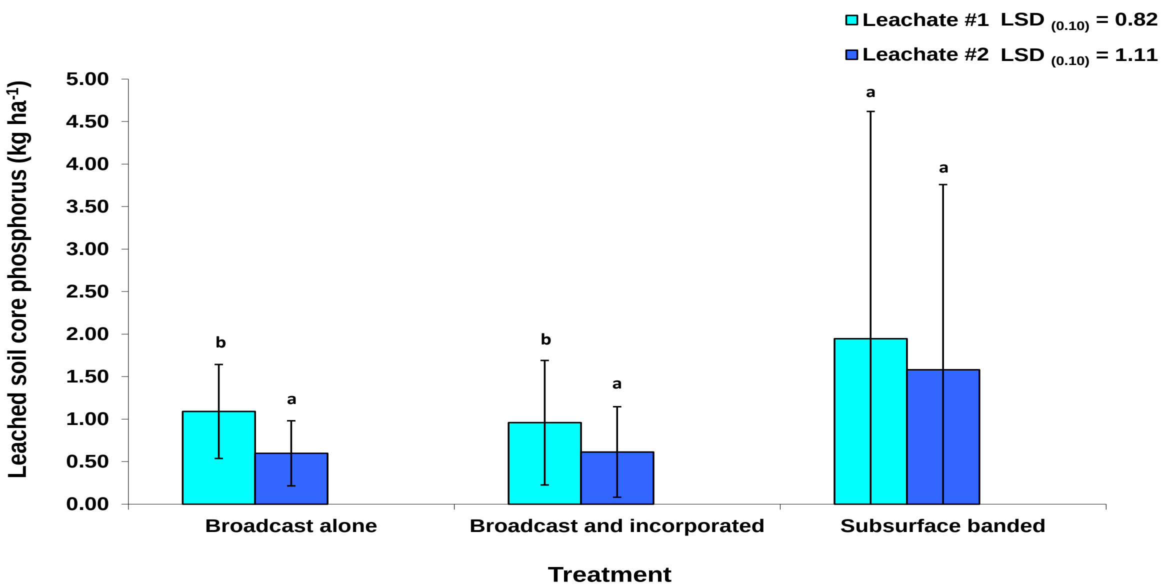

Fig. 5.4. Orthophosphate-P removed in two, 5-cm leaching events of intact soil cores (0-15 cm) collected from plots receiving high solid cattle manure application rate (60 t ha^{-1}). Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviation of the mean.

Compared to P removal in simulated snowmelt reported in Chapter 4, where removal of P was in the order of ~ 0.1 to 0.5 kg P ha^{-1}, the amounts of P removed by downward leaching through the 0- 15 cm depth of soil were greater. Eghball (2003) observed that after four years of N-based SCM application, and disking after each application to a depth of 10 cm, leaching of P was observed at the 30 cm depth. Unfortunately, in the current study it was not practical to press in the PVC cores beyond a depth of 15 cm, due to excessive compaction. Increased interaction between water and P containing constituents in the soil could explain the greater P removal in the core leaching. Ashjaei et al. (2010) reported that in leaching studies conducted on intact soil cores removed from eight-year 400 kg N ha^{-1} SCM rate treatments, the amount of labile P leached was significantly greater than the unamended control treatment and significantly higher than LHM treated plots, reflecting the greater P content in applied SCM. In the current study, the amounts of orthophosphate removed in the second leaching event was less than in the first leaching. This would be expected as the most soluble P constituents of manure are readily removed by plant uptake or leaching (Qian and Schoenau, 2000), leaving more recalcitrant, less soluble forms behind. It also suggests that for SCM, the higher P and OM content, duration of application and amount of SCM added can make a significant contribution of P to soil, not only in the inorganic labile form, but through subsequent mineralization of organic P.

The results from the subsurface banded SCM treatment have a greater variability than the broadcast alone and broadcast and incorporated SCM treatments, possibly as a result of greater microscale sampling variability created when attempting to sample in the manure subsurface band. Large microscale (cm and m distances) variability has also been reported in soil extractable PO_4-P and NO_3-N in no-till fertilized fields as a consequence of residual fertilizer bands (Hu et al., 2014). Considering the two leaching events combined, subsurface banding of SCM results in greater orthophosphate leaching compared to the broadcast alone and broadcast and incorporated SCM application methods.

The placement of SCM in a sub-surface band concentrates the SCM and reduces the interaction between the manure P and the soil constituents. Kar et al. (2012) used XANES spectroscopy to reveal that much of the P found in bands of cattle manure was present as relatively soluble brushite at the center of the band compared to apatite extending further away from the band center, a consequence of reduced interaction of P with soil calcium near the band center. The broadcast alone SCM application method spreads the SCM over the soil surface, with greater distance between the source of the P and exit at the bottom of the core. The broadcast and incorporated application mixes a portion of the SCM with the upper soil profile, distributing the manure throughout the soil volume and maximizing contact with soil constituents like clays and carbonates that can fix manure P. During seeding operations, there would be further soil mixing in the broadcast and incorporated treatment, and some SCM incorporation into the upper soil profile in the broadcast alone application method. With some soil incorporation occurring with the broadcast alone and broadcast and incorporation application methods, more of the P in the SCM is also in contact with soil and removed from solution by reaction with clay, OM and calcium compounds, thus making the P less prone to leaching.

Danish researchers (Heckrath et al., 2002) reported that dissolved OC and P measured in water leachate from intact soil columns collected from cattle manured soils was due to transport through macropore flow, also termed “preferential” flow. High rainfall events can cause water to move by preferential flow (Armstrong et al., 1999; Scott et al., 1998) and under this condition, more P can be found in leachate water (Scott et al., 1998; Simard et al., 2000; Stamm et al., 1998).

The presence of preferential flow paths could allow P to avoid adsorption sites in the subsoil and could possibly be a reason for higher amounts of P to be found in water leachate (Butler and Coale, 2005). Rapid movement through the soil by water and avoiding adsorption zones, could be responsible for greater P concentration in water leachate (McDowell et al., 2002). Kleinman et al. (2005) reported the downward movement of P through macropore channels as the preferred flow pathways in leaching of intact soil cores. However, subsurface banding of manure seems more likely to result in preferential flow paths for horizontal, lateral transport, enhancing surface and subsurface lateral flow during snowmelt run-off, rather than vertical transport processes in core leaching. As such, creation of preferential flow paths could be a viable explanation for the enhanced removal of P from the 0-15 cm depth by downward percolating water in subsurface banded treatments, since the creation of a band opening in the soil during SCM placement, creates a preferential flowpath extending to within 5 to 2 cm of the leaching depth.

While passing of water through the upper surface can transfer P to depth due to desorption to the water leachate (Gachter et al., 2004), some of the mobilized P may then be removed from soil solution further down in the profile. Brock et al. (2007) reported that on long-term 40-year dairy and poultry manured fields in southern New York state, the mean dissolved reactive P collected from leached intact soil cores ranged from 0.007 kg P ha^{-1} in dairy manure treated plots to 0.055 kg P ha^{-1} in poultry manure treatment plots. The reported amounts of P leached from the cores in their study are much smaller than the amounts observed in this study which may be explained by a much longer core length (52 cm) that would allow for manure P originating near the surface to react with adsorbing surfaces and be removed from the water before it exits the core bottom. Brock et al. (2007) indicated that rapid preferential flow was the principal mechanism allowing for the rapid movement of water through the soil core and could account for the amount of P in the leachate water.

For NO_3-N in the first leaching event, the subsurface banded and broadcast and incorporated 60 t ha^{-1} rate manure treatments had removal of 0.93 and 0.92 kg N ha^{-1} of NO_3-N, respectively, via the water percolating through the intact soil cores (Fig. 5.5). The amount of nitrate leached from the subsurface banded and broadcast and incorporated SCM treatments was significantly higher than measured in the broadcast alone application method treatment (0.56 kg NO_3-N ha^{-1}). Likewise, with the second leaching event, leached NO_3-N in the subsurface banded and broadcast and incorporated SCM treatments was 0.33 and 0.31 kg N ha^{-1}, respectively; greater than the 0.15 kg ha^{-1} measured in the broadcast alone treatment (Fig. 5.5). Greater leached nitrate in treatments where manure is in the soil versus on the surface may arise as a result of greater decomposition, mineralization and nitrification when manure is placed in the soil.

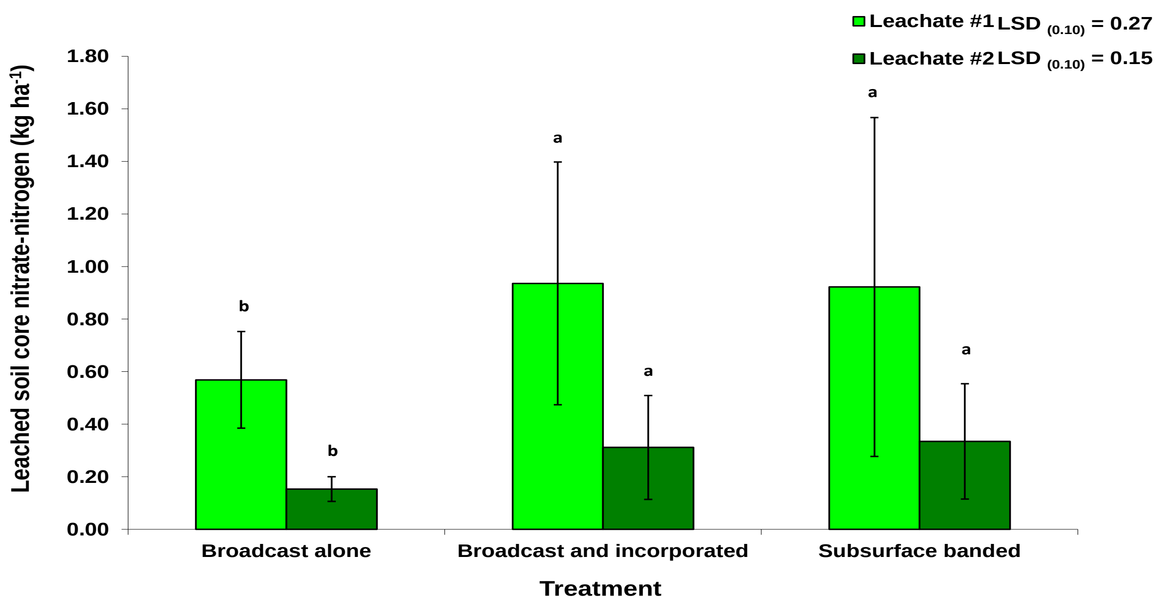

Fig. 5.5. Nitrate nitrogen removed in two, 5-cm leaching events of intact soil cores (0-15 cm) collected from plots receiving high solid cattle manure application rate (60 t ha^{-1}). Means followed by the same letter are not significantly ($P \leq 0.10$) different. Error bars are standard deviation of the mean.

Nitrate is considered a mobile anion that is not adsorbed to soil colloids whereas phosphate is strongly sorbed (Havlin et al., 2014). Despite the high leachability of NO_3-N, the observed lower amounts of NO_3-N leached than SRP in these manured soils reflects a low content of nitrate in the manure and a limited release of inorganic N through mineralization of cattle manure N in the short-term (Mooleki et al., 2004). The NO_3-N transported downward in the soil profile by water movement in the subsurface banded and broadcast and incorporated treatments in the second leaching event was less than one-half of that found in the first leaching event, suggesting limited NO_3-N replenishment in contrast to P, where replenishment by desorption can explain P removals in the second leaching event that are about 60 to 80% of that removed in the first leaching. Nitrate-N can be easily transported by water down in the soil profile as it is not readily adsorbed onto soil adsorption sites. The greater mobility of NO_3-N compared to P may explain why measured NO_3-N was similar in the broadcast and incorporated and subsurface banded treatments.

5.6 Conclusion

The removal of OC and N, PO_4-P and NO_3-N from the 0-15 cm depth of soil by percolating water was markedly affected by the method of placement of SCM. Specifically the subsurface banded SCM placement method resulted in significantly greater nutrient export compared to the broadcast placement of manure. Nitrate-N leached from the subsurface banded treatment was similar to the broadcast and incorporated treatment, and was significantly greater compared to the broadcast alone treatment. Placement of SCM in a concentrated band at the 10-13 cm depth would decrease contact with soil mineral and organic adsorption site components; thereby resulting in greater movement of nutrient with percolating water below the 15 cm depth. In-soil placement could also increase the rate of microbial activity and organic decomposition, accelerating the transformation of the nutrient into more soluble lower molecular weight and inorganic forms. Overall, the effect of placement was most significant for nutrient transport with water via downward leaching, versus the limited effect observed for manure placement on surface run-off and shallow subsurface lateral flow (see Chapter 4). This is a phenomena best explained by the greater interaction of water with soil in a leaching versus surface run-off scenario. Movement of nutrient below the surface horizon (0-15 cm) into the soil beneath may result in reduced root access in the early stages of growth for annual crops, and also potentially increase microbial activity at depth as a source of C and nutrient ions enters from above.

Greater movement below the 15 cm depth when SCM is banded could affect nutrient fate by affecting the rate of important transformations like mineralization, nitrification and denitrification, as well as reduce the amount of available P and NO_3-N that the roots can access. Future research would be recommended to investigate movement to a greater depth in the profile, such as to the top of the C horizon. This is challenging but may be possible in some instances using carefully inserted cores or nests of lysimeters. It would also be desirable to follow the fate of the nutrient once it is transported to greater depth, in particular sorption, mineralization-immobilization and denitrification processes. This experimentation could include amending different soil textures (coarse sandy soil vs. fine clay soil) from different Saskatchewan soil climatic zones using the above mentioned SCM application technologies and differing rates of application.

6. OVERALL SYNTHESIS AND CONCLUSIONS

6.1 Summary of Findings and Their Importance

In the studies that were completed and described in this thesis (Chapters 3, 4 and 5), new placement technologies were investigated that specifically relate to in-soil manure placement in bands in comparison to conventional broadcast or broadcast and incorporate placements. In-soil placement of solid cattle manure (SCM) in bands had a relatively small, but positive, impact on crop yield and nutrient uptake in a three-year crop rotation in east-central Saskatchewan compared to broadcast alone, and broadcast and incorporation application strategies. Increasing the rate of SCM in broadcast alone, broadcast and incorporated and subsurface banded application methodologies had a small effect on increasing crop yields, especially in the initial years of the study.

The addition of SCM to soil increased nutrient export in run-off and leachate compared to the unamended control. Solid cattle manure application rate and placement method had no impact on the release of nutrients from crop residues to leachate water. In-soil placement of SCM was also not effective in reducing soluble reactive phosphorus (SRP) and nitrogen (N) export from soil in snowmelt runoff and leachate water compared to broadcast application. Twelve years of subsurface placement of liquid hog manure (LHM) resulted in a SRP export rate about ten times lower than SRP export in SCM amended plots, in water runoff and leachate. Nitrate-N export in water running across frozen soil surface in broadcast and incorporated plots was higher than in non-manured SCM plots. Despite the higher amount of N added with LHM, and the longer application period (twelve-year LHM study versus three-year SCM study) nitrate-N (NO_3-N) export in runoff and leachate snowmelt water was similar in SCM and LHM amended plots. Neither LHM or SCM treatment application methodology and/or application rates had any differing effect on ammonium N (NH_4-N) export in runoff water. Export of P and N downward through the soil in leachate water, as assessed in intact surface (0-15cm) soil cores collected from the field trials, was actually increased by in-soil manure placement, especially in subsurface bands.

Placement of SCM in subsurface bands creates preferential flow paths through which mobile nutrients like NO3-N can be more easily transported downward in the soil profile. Less mobile nutrients such as P could also be transported by water movement, especially if there is an excess of nutrient that is not bound in the soil mineral or organic faction. Overall, nutrient export in run-off was significantly lower in frozen versus thawing soils, and export of P in soils receiving LHM was much less than in soils receiving SCM.

In general, the research described in this thesis provides new insight into how the application of manure to soil influences crop response and the potential export of nutrient off-site in surface and sub-surface water flow in prairie soils. A new technique involving the collection of intact slabs of soil from replicated research plots and exposing them to simulated snowmelt run-off was developed and successfully employed. A technique was also developed for collection of intact soil cores from plots that was then used to assess leaching under conditions closely resembling that of the field.

Practically, the knowledge obtained from these studies can be used to develop and refine recommendations for beneficial manure management. For example, SCM poses more concern than LHM for export of soluble P, and when dealing with concerns of transport of soluble P and N over short distances (cm or m) in the soil, sub-surface placement of manure may be undesirable. Furthermore, agronomic and environmental benefits to be gained by the development of sophisticated and expensive equipment for banding SCM on the prairies may be limited. Based on results obtained, runoff water passing across the surface of frozen manured soil is anticipated to result in less soluble nutrient removed compared to thawing soil, but may also result in transport of the nutrient in the water further away. Surface water contamination risks are likely to be influenced by conditions during snowmelt as well as topography and the type, rate and method of application of manure.

Overall, this PhD research furthered our basic understanding of SCM and LHM application and its relationship to nutrient fate in several ways, including:

Crop and soil nutrients. The application of SCM using broadcast alone, broadcast and incorporated and subsurface banding at rates of 20.2, 40.4 and 60.6 t ha^{-1} increases yield but the greatest yield responses may be obtained when SCM is combined with urea fertilizer. Yield responses to SCM are limited in the initial years of application due to the low availability of the manure N. It is expected that in-soil placement of manures that are higher in NH_4-N content than used in this study are likely to show more benefit from in-soil placement, due to greater potential for volatile ammonia losses when surface placed. Soil extractable available P in the 0-15 cm depth increased substantially during the three years of SCM application. At the end of the three year study, soil supply of P at the soil surface was greater in the broadcast alone placement treatment, compared to the broadcast and incorporated and subsurface banded treatments, indicating that surface placement of manure does increase P stratification in the soil. Canola plant residues collected from the surface of the manured plots also demonstrated enhanced loss of P when exposed to water leaching compared to non-manured treatment, which may also contribute to P export off-site. The limited effect on crop yield and plant nutrient uptake using the subsurface banded methodology, compared to the commonly practiced broadcast method, combined with the need for specialized subsurface banding equipment would seem to render the use of the SCM banding methodology economically impractical in applying SCM. Although no economic analysis utilizing subsurface banding technology was made, it would seem probable that the expense required in acquiring (i.e., purchasing, renting, hiring custom applicator) specialized technology for applying SCM in this manner would not be offset through provision of tangible agronomic benefits.

Export of nutrient in snowmelt water. The application of SCM, whether as broadcast alone, broadcast and incorporated or subsurface banded significantly increased the transport of SRP in snow covered thawing soil slabs. More significant was that there was no discernable effect of placement method on SRP transport amongst the three SCM application methodologies evaluated, despite greater exchangeable P content observed in the top 1 cm of soil when the cattle manure was broadcasted. The incorporation of SCM and/or subsurface band placement methodologies may not be effective in reducing nutrient export, and could actually increase the production of SRP by enhancing decomposition of the manure and increased preferential flow of water through channels created by the banding. The application of SCM also enhanced export of SRP in run-off collected from water flowing over frozen soil slabs but, as for snowmelt on thawing soils, there was no significant effect of placement method. It is noteworthy that the amounts removed by water flowing across frozen soil was less than half of the exported SRP in snow covered thawing soil slabs. In snow covered thawing soil slabs amended after 12 years of subsurface banded LHM, the amount of run-off and leachate had approximately ten times less SRP compared to the SCM amended snow covered thawing soil slabs. This is explained by a lower P load in relation to crop removal over the study period in the LHM treatments, continued crop uptake and removal, and may also reflect a reduction in manure derived soil P solubility over the long-term in the LHM amended soils. For the SCM, there was no discernable effect of manure application method or even rate on NO_3-N export, unlike SRP export. Twelve-year applications of high rate LHM did create an accumulation of NO_3-N in the soil, which resulted in higher NO_3-N export in snow covered thawing soil slab run-off in LHM amended soil. Rapid transformation of NH_4-N to NO_3-N by nitrification, adsorption of NH_4-N to soil cation exchange sites and crop uptake could explain why there were only small amounts of exported NH_4-N in run-off water in the manure treatments.

Export of nutrient in leaching water. The removal of OC, total N, PO_4-P and NO_3-N from the 0-15 cm depth of intact soil columns collected from SCM manure treatments in the field was affected by the SCM placement methodology. Overall, there was greater nutrient export by leaching in the subsurface SCM banded treatments compared to the broadcast alone treatment. Nitrate-N export in the manure subsurface banded treatment was similar to the broadcast and incorporated treatment, and greater than NO_3-N removal in the broadcast alone treatment. By placing the SCM in a concentrated band at a depth of 10-13 cm, the concentrated band may decrease fixation by reducing contact between manure nutrient ions and the soil mineral and organic components and therefore increase potential for downward water transport of nutrients from the top 15 cm of the soil profile. As well, the subsurface placement could also enhance the decomposition and release of nutrient from complex, insoluble P and N containing organic forms in the manure. Overall, there was a significant effect of manure placement on nutrient export with downward leaching water compared to snowmelt water moving across and downward in a thawing soil slab. The greater interaction of water with the manure and soil constituents as it passes downward would explain the greater effect on nutrient export compared to water moving across a soil surface.

6.2 Future Research

Research on the application of SCM and LHM to agricultural fields and its effects on crops and soils has been conducted for many years. The research described in this thesis adds to this body of research. The findings contribute practically to the development of recommendations for best manure management practices that will maximize agronomic benefit and reduce nutrient entry to atmosphere and water. Our basic understanding of the fate of land applied manure nutrients as affected by manure management practices and environmental conditions is improved. The recommendations for best manure management in use today are based on research work that has directly assessed the impact, such as effect of manure placement on crop yield, nutrient recovery and soil residual nutrients; the impact on gaseous emissions of C (e.g., carbon dioxide and methane) and N (e.g., ammonia, nitrous oxide) to the atmosphere; and export of P and N with water (emphasized in this Ph.D research). While in-soil placement is generally recommended, because it has proven beneficial for liquid manures in increasing crop nutrient recovery and reducing ammonia losses, recent work has shown that it can increase nitrous oxide contribution. The results of this thesis research show that while in-soil placement of solid cattle manure may also enhance yield and nutrient recovery compared to surface placement, it may not be effective in reducing export off-site with water. This Ph.D work has sought to examine the effects on crop production, plant nutrient uptake and residual soil and residue nutrients while at the same time also looking at the effect that manure placement methodologies have on P and N nutrient export with water under conditions representing different scenarios for water movement in Canadian prairie soil. However, there are still research gaps that need to be addressed and further examined.

6.2.1 Documenting the impact of manure placement on soil biological activity and decomposition in the manure application zone.

Placement of manure in the soil is anticipated to increase microbial decomposition of the organic component of the manure, as has been observed in past research with incorporated crop residues versus surface placed. This is because of greater contact between manure and microbial constituents and more favorable water regime for decomposition. However, the impact of banding of manure in soil is less certain. Areas of high manure concentration could favor microbial activity because of the high OM content but abundance of nutrient ions like NH_4-N that are toxic in high concentrations, along with osmotic impact of manure salts could also have a negative effect. This is an unknown that should be addressed. Measurement of microbial populations, respiration (carbon dioxide production) and the pattern of release of soluble constituents on a microscale (cm) in intact soil monoliths collected from different placement techniques would be valuable. Infiltration measurements and tracing of water flow pathways as affected by manure placement would also be beneficial.

6.2.2 Investigating nutrient dynamics and movement at greater soil depth

The research work covered in this thesis is concentrated on manure nutrient fate and mobility in the top 0-15 cm depth, which in many cultivated prairie soils encompasses the Ap horizon. Investigation of nutrient movement and transformations below 15 cm is warranted in SCM sub-surface banded soil. Nutrient transformations such as mineralization, nitrification and denitrification occur in both surface and subsurface horizons, albeit at a slower rate with greater depth in the profile. Transport of manure nutrient with water below the 30 cm depth may occur in some soils associated with a large rainfall event. Deep leaching may occasionally occur in wet years and in specific areas of the landscape such as depressions. Plant root access and uptake of subsurface banded nutrients that are potentially released and moved to greater depths should be examined in differing soil textures (coarse sandy soil vs. fine clay soil) that commonly occur in Saskatchewan, with comparisons made to other placement methods. This research could be conducted on soils of varying texture from different Saskatchewan soil climatic zones using soil cores taken to greater soil depths (i.e., 60 cm or to the top of the C horizon).

The incorporation of SCM using subsurface banding methodology may not be effective in reducing nutrient transport as the placement in a concentrated band may reduce manure contact with soil constituents, slowing SRP and NH_4-N adsorption that removes these ions from the soil water. Nutrient transformation functions such as mineralization, nitrification and denitrification processes could be investigated at predefined depth intervals under SCM subsurface bands. This could be examined using vertically obtained soil monoliths excavated to a deeper depth to measure these processes. This would increase our knowledge regarding the fate of nutrients as affected by transformations at greater depth than in the current study.

The placement of high rates of LHM in concentrated bands has led to accumulations of NO_3-N at soil depths extending over 100 cm in a soil profile (Mooleki et al., 2002). While SCM is low in available NH_4-N and contains lower amounts of organic N, SCM does contain greater amounts of P that over time can be mineralized into mobile SRP. One of the limitations of this study was the placement of PRS™ probes under the soil surface at a depth of ~ 1 cm. A soil profile vertically excavated to a depth of 60 cm and placement of plant root simulator probes at 5 cm intervals would aid in understanding the distribution of readily exchangeable manure nutrients at deeper depths under subsurface banded SCM.

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APPENDIX A. DIXON, SASKATCHEWAN SITE PLOT MAPS

Block 4	9 9	7 7	10 10	13 13	3 3	4 4	8 8	11 11	12 12	6 6	1 1	5 5	2 2	14 14	15 15
	43	44	45	46	47	48	49	50	51	52	53	54	55	56	60
Block 3	11 11	4 4	12 12	3 3	10 10	6 6	5 5	14 14	7 7	9 9	2 2	8 8	13 13	1 1	15 15
	29	30	31	32	33	34	35	36	37	38	39	40	41	42	59
Block 2	14 14	7 7	1 1	2 2	4 4	5 5	8 8	12 12	3 3	11 11	6 6	10 10	9 9	13 13	15 15
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	58
Treatment #															
Block 1	7 7	4 4	5 5	6 6	11 11	9 9	12 12	3 3	1 1	8 8	14 14	13 13	10 10	2 2	15 15
Plot # →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	57

	Treatment	Treatment rate (t ha^{-1})
1	Control	0
2	Disturbed Control	0
3	Broadcast & Incorporated	20
4	Broadcast & Incorporated	40
5	Broadcast & Incorporated	60
6	Broadcast alone	20
7	Broadcast alone	40
8	Broadcast alone	60
9	Subsurface banded	20
10	Subsurface banded	40
11	Subsurface banded	60
12	Subsurface banded plus urea fertilizer	20 plus (78 kg N ha^{-1})
13	Subsurface banded plus urea fertilizer	40 plus (78 kg N ha^{-1})
14	Subsurface banded plus urea fertilizer	60 plus (78 kg N ha^{-1})
15	Urea fertilizer	78 kg N ha^{-1}

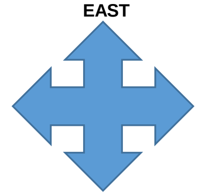

Fig. A.1. Three-Year Solid Cattle Manure Study Plot Map and Treatments

	Block 3															Block 4														
Plot #	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Treatment #	**9**	**5**	**13**	**10**	**7**	**15**	**2**	**4**	**14**	**12**	**8**	**3**	**11**	**1**	**6**	**14**	**13**	**10**	**2**	**9**	**15**	**5**	**12**	**7**	**4**	**8**	**1**	**3**	**6**	**11**

	Block 1															Block 2														
Treatment #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**6**	**2**	**8**	**10**	**13**	**3**	**14**	**12**	**1**	**11**	**15**	**7**	**9**	**4**	**5**
Plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Treatment	**Treatment rate (L ha^{-1})**
1. Check-No Injector Pass	0
2. Check- Injector Pass at 12"	0
3. Subsurface banded 12"	37000
4. Subsurface banded 12"	37000
5. Subsurface banded 12"	74000
6. Subsurface banded 12"	74000
7. Subsurface banded 12"	74000
8. Subsurface banded 12"	148000
9. Subsurface banded 12"	148000
10. Subsurface banded at 12" and nitrification inhibitor	37000
11. Manure and Water at 37,000 L ha^{-1}	37000
12. Broadcast and 24 h delayed incorporation	37000
13. Banded Urea	56 kg ha^{-1}
14. Banded Urea	112 kg ha^{-1}
15. Banded Urea	224 kg ha^{-1}

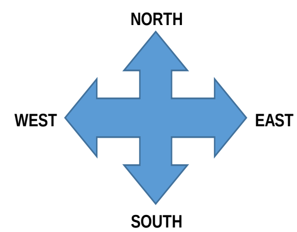

Fig. A.2. Twelve-Year Liquid Hog Manure Study Plot Map and Treatments

APPENDIX B. DIXON, SASKATCHEWAN PLANT, SOIL AND RUNOFF AND/OR LEACHATE CONCENTRATION DATA

Table B.1. Straw biomass (kg ha^{-1}) in 2007 (oats), 2008 (canola) and 2009 (oats) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	3120†	(1306)‡	1702	(619)	2248	(774)
Control-Disturbed	**0**	3321	(1168)	1608	(1229)	2414	(793)
	20.2	4017	(495)	2539	(1092)	3282	(572)
Broadcast alone	**40.4**	4474	(631)	2706	(573)	4020	(384)
	60.6	4877	(1884)	3252	(429)	5031	(598)
	20.2	4419	(643)	2776	(526)	3473	(674)
Broadcast and incorporated	**40.4**	4699	(395)	3294	(700)	4172	(746)
	60.6	4604	(951)	3154	(646)	5031	(660)
	20.2	4196	(602)	2074	(437)	4505	(820)
Subsurface banded	**40.4**	4567	(249)	2840	(978)	5361	(840)
	60.6	4493	(1266)	3539	(774)	5573	(992)
	20.2 + urea	5028	(813)	4840	(711)	5507	(844)
Subsurface banded + urea	**40.4 + urea**	5418	(766)	4543	(719)	6534	(609)
	60.6 + urea	5686	(708)	5188	(1073)	6170	(481)
Urea	**78 kg N ha^{-1}**	4782	(445)	3408	(850)	5186	(561)
$LSD_{(0.10)}$§		657		634		552	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

Table B.2. Straw phosphorus concentrations (μg P g^{-1} of dry matter) in 2007 (oats), 2008 (canola) and 2009 (oats) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(μg g^{-1})			
Control	**0**	1002†	(634)‡	854	(372)	2032	(143)
Control-disturbed	**0**	914	(285)	912	(344)	1926	(468)
	20.2	986	(125)	659	(119)	2111	(618)
Broadcast alone	**40.4**	1097	(169)	692	(258)	2294	(208)
	60.6	1256	(161)	799	(147)	2525	(402)
	20.2	1034	(134)	734	(129)	3095	(1833)
Broadcast and incorporated	**40.4**	1558	(304)	642	(266)	2346	(321)
	60.6	1447	(429)	1056	(373)	2178	(80)
	20.2	906	(80)	813	(495)	1708	(324)
Subsurface banded	**40.4**	1129	(285)	741	(396)	1727	(116)
	60.6	1352	(417)	647	(239)	2155	(135)
	20.2 + urea	795	(174)	562	(104)	1394	(304)
Subsurface banded + urea	**40.4 + urea**	1057	(334)	622	(194)	1788	(147)
	60.6 + urea	1129	(314)	749	(78)	2022	(80)
Urea	**78 kg N ha^{-1}**	557	(18)	531	(15)	1001	(273)
$LSD_{(0.10)}$§		352		329		644	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

Table B.3. Straw nitrogen concentrations (µg N g^{-1} of dry matter) in 2007 (oats), 2008 (canola) and 2009 (oats) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(µg g^{-1})			
Control	**0**	1522[†]	(476)[‡]	2794	(1757)	1615	(839)
Control-disturbed	**0**	1680	(492)	2449	(1289)	1823	(288)
	20.2	1504	(158)	1556	(539)	2205	(1533)
Broadcast alone	**40.4**	1836	(257)	1618	(395)	1591	(257)
	60.6	1708	(676)	1665	(498)	1961	(385)
	20.2	1992	(475)	1833	(280)	1265	(277)
Broadcast and incorporated	**40.4**	2225	(556)	1731	(455)	1569	(528)
	60.6	1896	(479)	2474	(963)	1928	(466)
	20.2	1484	(292)	2177	(911)	1140	(90)
Subsurface banded	**40.4**	1670	(164)	1619	(595)	1847	(267)
	60.6	2014	(1032)	1429	(148)	2477	(549)
	20.2 + urea	3562	(561)	2263	(812)	3257	(557)
Subsurface banded + urea	**40.4 + urea**	4215	(263)	2080	(552)	4175	(933)
	60.6 + urea	5061	(622)	2440	(437)	6307	(1432)
Urea	**78 kg N ha^{-1}**	2765	(255)	1981	(229)	2214.4	(555)
$LSD_{(0.10)}$[§]		1216		363		863	

[†] Means in the first column

[‡] Standard deviation (±) of the means in the second column

[§] Least significant difference at $P \leq 0.10$

Table B.4. Soil extractable phosphorus (kg ha^{-1}) (15-30 cm depth) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	4.8†	(0.4)‡	3.5	(1.4)	4.0	(0.5)
Control-disturbed	**0**	4.6	(0.4)	3.4	(1.2)	4.2	(0.6)
	20.2	5.1	(0.3)	4.0	(1.4)	5.4	(1.9)
Broadcast alone	**40.4**	5.3	(0.5)	5.3	(1.7)	6.4	(2.2)
	60.6	6.5	(0.7)	11.0	(12.0)	8.6	(3.3)
	20.2	4.8	(0.3)	5.2	(2.0)	5.0	(0.6)
Broadcast and incorporated	**40.4**	4.9	(0.2)	5.3	(1.7)	6.9	(2.7)
	60.6	5.9	(1.0)	5.4	(1.6)	8.4	(1.2)
	20.2	5.0	(0.2)	4.1	(0.6)	4.3	(0.6)
Subsurface banded	**40.4**	5.5	(0.8)	5.6	(1.9)	8.7	(1.3)
	60.6	5.8	(1.6)	6.0	(1.6)	7.8	(5.1)
	20.2 + urea	4.5	(0.3)	4.6	(1.8)	5.7	(1.4)
Subsurface banded + urea	**40.4 + urea**	5.2	(0.4)	5.0	(1.4)	9.4	(8.5)
	60.6 + urea	5.8	(0.9)	14.6	(17.9)	7.0	(2.4)
Urea	**78 kg N ha^{-1}**	4.6	(0.8)	4.0	(1.2)	5.1	(0.9)
LSD$_{(0.10)}$§		0.8		6.7		3.7	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

Table B.5. Soil extractable nitrate-nitrogen (kg ha^{-1}) (15-30 cm depth) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	4.7†	(1.0)‡	2.9	(1.1)	4.2	(0.4)
Control-disturbed	**0**	4.3	(0.7)	2.8	(0.6)	3.7	(0.4)
	20.2	4.1	(0.6)	2.2	(1.9)	4.8	(1.5)
Broadcast alone	**40.4**	5.2	(1.5)	3.3	(0.8)	5.3	(1.2)
	60.6	4.4	(0.8)	3.9	(1.3)	5.8	(0.9)
	20.2	4.5	(0.3)	2.4	(0.8)	3.8	(0.4)
Broadcast and incorporated	**40.4**	4.9	(1.3)	2.8	(1.3)	4.5	(0.6)
	60.6	4.7	(1.6)	3.2	(0.6)	4.9	(0.8)
	20.2	4.9	(0.5)	2.8	(1.3)	4.2	(0.7)
Subsurface banded	**40.4**	4.4	(0.2)	2.7	(1.0)	4.7	(0.8)
	60.6	4.6	(1.1)	1.9	(1.2)	5.5	(0.2)
	20.2 + urea	4.7	(0.7)	3.2	(1.5)	5.3	(0.5)
Subsurface banded + urea	**40.4 + urea**	4.6	(0.5)	3.5	(0.7)	9.8	(2.6)
	60.6 + urea	5.7	(1.6)	6.3	(3.0)	15.2	(6.4)
Urea	**78 kg N ha^{-1}**	3.6	(0.4)	5.2	(1.7)	4.9	(0.6)
$LSD_{(0.10)}$§		0.9		1.2		2.2	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

Table B.6. Soil extractable ammonium-nitrogen (kg ha^{-1}) (15-30 cm depth) in three-year solid cattle manure study at Dixon, Saskatchewan.

	Application rate	2007		2008		2009	
	(t ha^{-1})			(kg ha^{-1})			
Control	**0**	7.3†	(1.7)‡	14.5	(3.7)	8.9	(2.4)
Control-disturbed	**0**	9.0	(3.5)	14.0	(3.3)	9.5	(0.9)
	20.2	8.3	(2.7)	12.3	(1.4)	9.1	(2.9)
Broadcast alone	**40.4**	7.2	(3.3)	13.6	(1.1)	8.4	(0.9)
	60.6	11.4	(4.0)	13.8	(5.9)	7.3	(0.8)
	20.2	9.0	(3.0)	16.5	(4.7)	8.7	(1.3)
Broadcast and incorporated	**40.4**	9.0	(2.3)	12.7	(1.7)	7.2	(1.1)
	60.6	7.5	(1.9)	14.2	(5.7)	8.6	(2.3)
	20.2	6.5	(3.0)	14.3	(2.4)	9.3	(2.7)
Subsurface banded	**40.4**	10.3	(4.6)	13.1	(2.9)	8.3	(3.1)
	60.6	8.6	(2.8)	10.3	(4.2)	7.5	(0.9)
	20.2 + urea	8.0	(3.0)	13.9	(3.3)	7.6	(1.3)
Subsurface banded + urea	**40.4 + urea**	9.2	(4.1)	22.5	(14.8)	7.2	(1.9)
	60.6 + urea	9.1	(3.5)	9.8	(4.0)	7.5	(1.0)
Urea	**78 kg N ha^{-1}**	9.5	(1.4)	17.0	(5.3)	9.5	(2.3)
$LSD_{(0.10)}$§		2.5		6.3		2.1	

† Means in the first column

‡ Standard deviation (±) of the means in the second column

§ Least significant difference at $P \leq 0.10$

Table B.7. Concentrations of soluble reactive phosphorus (μg P ml^{-1}), dissolved nitrate-nitrogen (μg NO_3-N ml^{-1}) and dissolved ammonium-nitrogen (μg NH_4-N ml^{-1}) in snowmelt from thawing soil slab monoliths from a three-year solid cattle manure field study collected in fall 2008.

Treatment† (t ha^{-1})	Block‡	Runoff and/or leachate collected§ (g)	PO_4-P¶	NO_3-N# (μg ml^{-1})	NH_4-N††	Application method
0	1	1069.1	0.5	10.7	0.2	with no incorporation, but disturbance‡‡
	2	462.1	0.2	4.5	0.3	
	3	391.6	1.2	7.4	0.2	
	4	292.6	0.5	3.5	0.1	
60.6	1	123.1	2.7	17.5	0.5	broadcast only
	2	435.9	5.4	10.4	0.3	
	3	651.2	1.0	13.3	0.1	
	4	802.8	3.5	7.6	0.4	
60.6	1	244.4	7.5	3.0	0.4	broadcast and incorporated
	2	758.9	3.4	13.1	0.4	
	3	895.8	3.5	9.6	0.4	
	4	819.5	3.1	10.7	0.5	
60.6	1	846.3	6.7	10.1	0.8	subsurface banded
	2	577.3	4.8	3.3	0.4	
	3	328.4	13.5	9.1	0.3	
	4	160.8	0.1	14.1	0.4	

† Application rate based on wet weight
‡ Block number in randomized complete block design
§ Runoff and/or leachate collected from snow melting on a thawing soil slab monolith
¶ Soluble reactive phosphorus
# Dissolved nitrate-nitrogen
†† Dissolved ammonium-nitrogen
‡‡ No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

Table B.8. Concentrations of soluble reactive phosphorus (µg P ml^{-1}), dissolved nitrate-nitrogen (µg NO_3-N ml^{-1}) and dissolved ammonium-nitrogen (µg NH_4-N ml^{-1}) in snowmelt from thawing soil slab monoliths from a three-year solid cattle manure field study collected in fall 2009.

Treatment† (t ha^{-1})	Block‡	Runoff and/or leachate collected§ (g)	PO_4-P¶	NO_3-N# (µg ml^{-1})	NH_4-N††	Application method
0	1	453.0	0.5	25.8	0.4	with no incorporation, but di:
	2	948.0	0.9	32.3	0.3	
	3	1790.4	1.2	23.3	0.4	
	4	616.2	2.0	4.7	0.3	
60.6	1	928.1	7.7	39.1	0.4	broadcast only
	2	1307.6	4.6	43.5	0.4	
	3	1426.3	8.0	37.1	0.4	
	4	261.0	9.8	1.4	0.3	
60.6	1	1132.5	8.3	44.1	0.3	broadcast and incorporated
	2	1438.5	7.4	62.1	0.4	
	3	1137.7	2.1	33.9	0.4	
	4	480.6	12.5	4.4	0.5	
60.6	1	625.7	10.2	46.3	0.2	subsurface banded
	2	1107.4	9.3	37.0	0.4	
	3	1169.7	6.4	27.5	0.4	
	4	178.7	10.6	1.8	0.5	

† Application rate based on wet weight
‡ Block number in randomized complete block design
§ Runoff and/or leachate collected from snow melting on a thawing soil slab monolith
¶ Soluble reactive phosphorus
# Dissolved nitrate-nitrogen
†† Dissolved ammonium-nitrogen
‡‡ No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

Table B.9. Concentrations of soluble reactive phosphorus (μg P ml^{-1}), dissolved nitrate-nitrogen (μg NO_3-N ml^{-1}) and dissolved ammonium-nitrogen (μg NH_4-N ml^{-1}) in water moving rapidly across the surface of frozen soil slab monoliths from a three-year solid cattle manure field study collected in fall 2009.

Treatment† (t ha^{-1})	Block‡	Runoff collected§ (g)	PO_4-P¶	NO_3-N# (μg ml^{-1})	NH_4-N††	Application method
0	1	1472.6	0.5	1.0	0.3	with no incorporation, but disturbance‡‡
	2	875.3	0.6	1.9	0.3	
	3	882.7	0.4	0.7	0.3	
	4	1421.1	0.3	0.4	0.3	
60.6	1	1041.5	3.0	5.9	0.3	broadcast only
	2	1031.1	2.4	2.2	0.3	
	3	1040.6	1.8	3.1	0.3	
	4	1341.7	1.8	2.0	0.3	
60.6	1	962.2	1.7	5.4	0.3	broadcast and incorporated
	2	1020.7	3.1	6.9	0.4	
	3	692.7	1.8	4.6	0.3	
	4	887.9	3.4	4.6	0.3	
60.6	1	743.6	2.6	4.2	0.3	subsurface banded
	2	1063.2	2.3	3.7	0.4	
	3	579.3	2.4	4.3	0.3	
	4	962.7	2.8	3.5	0.3	

† Application rate based on wet weight
‡ Block number in randomized complete block design
§ Runoff and/or leachate collected from snow melting on a thawing soil slab monolith
¶ Soluble reactive phosphorus
# Dissolved nitrate-nitrogen
†† Dissolved ammonium-nitrogen
‡‡ No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

Table B.10. Concentrations of soluble reactive phosphorus (µg P ml^{-1}), dissolved nitrate-nitrogen (µg NO_3-N ml^{-1}) and dissolved ammonium-nitrogen (µg NH_4-N ml^{-1}) in snowmelt on thawing soil slab monoliths from a twelve-year liquid hog manure field study collected in fall 2009.

Treatment† (L ha^{-1})	Block‡	Runoff and/or leachate collected§ (g)	PO_4-P¶	NO_3-N# (µg ml^{-1})	NH_4-N††	Application method
0	1	2220.1	0.1	5.3	0.3	with no incorporation, but disturbance‡‡
	2	711.6	0.2	11.1	0.3	
	3	441.0	0.6	8.6	0.4	
	4	865.0	0.3	22.7	0.4	
37,000	1	1370.4	0.1	50.4	0.3	hog manure subsurface banded
	2	677.0	0.7	17.9	0.4	
	3	233.6	0.1	47.8	0.4	
	4	1078.7	0.5	26.4	0.4	
148,000	1	1045.6	0.7	29.7	0.3	
	2	1247.6	0.7	119.8	0.4	
	3	348.7	2.2	57.0	0.5	
	4	859.3	1.2	46.5	0.3	
37,000	1	593.3	0.4	49.6	0.3	hog manure broadcast and incorporated
	2	724.6	0.2	15.9	0.3	
	3	336.2	0.8	3.2	0.4	
	4	929.9	1.5	14.3	0.5	

† Application rate based on wet weight
‡ Block number in randomized complete block design
§ Runoff and/or leachate collected from snow melting on a thawing soil slab monolith
¶ Soluble reactive phosphorus
# Dissolved nitrate-nitrogen
†† Dissolved ammonium-nitrogen
‡‡ No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil

Table B.11. Concentrations of soluble reactive phosphorus (μg P ml^{-1}), dissolved nitrate-nitrogen (μg NO_3-N ml^{-1}) and dissolved ammonium-nitrogen (μg NH_4-N ml^{-1}) in water moving rapidly across the surface of frozen soil slab monoliths from a twelve-year liquid hog manure field study collected in fall 2009.

Treatment† (L ha^{-1})	Block‡	Runoff collected§ (g)	PO_4-P¶	NO_3-N# (μg ml^{-1})	NH_4-N††	Application method
0	1	1452.9	0.0	0.5	0.3	with no incorporation, but disturbance‡‡
	2	1689.8	0.0	0.1	0.3	
	3	1404.4	0.1	0.2	0.3	
	4	1264.6	0.1	1.1	0.3	
37,000	1	1727.3	0.1	0.5	0.3	hog manure subsurface banded
	2	1330.6	0.1	2.5	0.3	
	3	1597.4	0.0	0.2	0.3	
	4	1757.2	0.1	0.2	0.3	
148,000	1	1788.1	0.1	0.7	0.3	
	2	1351.6	0.2	11.5	0.3	
	3	1117.9	0.2	1.7	0.3	
	4	1375.4	0.2	2.9	0.3	
37,000	1	1366.1	0.2	5.8	0.3	hog manure broadcast and incorporated
	2	1704.2	0.0	0.0	0.3	
	3	1366.3	0.0	1.5	0.3	
	4	1330.2	0.1	2.1	0.3	

† Application rate based on wet weight
‡ Block number in randomized complete block design
§ Runoff and/or leachate collected from snow melting on a thawing soil slab monolith
¶ Soluble reactive phosphorus
# Dissolved nitrate-nitrogen
†† Dissolved ammonium-nitrogen
‡‡ No application of manure and soil disturbance with PAMI manure applicator coulters inserted in soil